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OFF-ROAD MOBILITY RESEARCH

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9 FEBRUARY 1967 - 8 AUGUST 1967
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GLOSSARY OF ACRONYMS AND CODE NAMES

ACTIV	Army Concept Team in Vietnam
AFV	Actual Forward Velocity
AGILE	Remote Area Conflict Research
AVLB	Armored Vehicle Launch Bridge
APC	Armored Personnel Carrier
ARPA	Advanced Research Projects Agency
CAL	Cornell Aeronautical Laboratory, Inc.
CAMERA	Computer Algorithm for Mathematical Extension of Running Areas
DDC	Defense Documentation Center
DOD	Department of Defense
FMC	Official Company Name (Formerly Food Machinery Corporation)
LLL	Land Locomotion Laboratory (of Army Tank-Automotive Command)
MACOV	Mechanized and Armored Combat Operations in Vietnam
MERS	Mobility Environment Research Study
NASA	National Aeronautics and Space Administration
OCRD	Office of the Chief of Research and Development
ORMR	Off-Road Mobility Research
PM	Phenomenological Model
R & T	Research and Technology
RCI	Rating Cone Index
RGV	Running Gear Velocity
SAE	Society of Automotive Engineers
SXP	Stream Crossing Problem
TECOM	Test and Evaluation Command
USCDC	United States Combat Development Command

GLOSSARY OF ACRONYMS AND CODE NAMES
(Continued)

VCI	Vehicle Cone Index
VSDM	Vehicle System Dynamics Model
VVOC	Vehicle Vertical Obstacle Capacity
WES	Waterways Experiment Station
WNRE	Wilson, Nuttall, Raimond, Engineers Inc.
WUL	Working Unit Level (a classification of form DD 1498)

1. INTRODUCTION AND SUMMARY

The desire to achieve transport capability suitable to military operations has forced engineers to replace traditional practice wherein environment is modified to accommodate ground supported vehicles with that of designing vehicles that will accommodate to the environment. A very substantial increase in the technological base is necessary to attain this objective.

Long development cycles for vehicles, high research and development costs, records of frequent vehicle breakdowns and extensive field maintenance are cited as a few examples where military performance and equipment cost-effectiveness can be significantly improved with expansion of the technological base.

The mobility limitations of U.S. military ground vehicles were dramatically brought to light when extreme operational difficulties were encountered in Vietnam. Mindful of the lack of effectiveness of our vehicles in Southeast Asia's demanding natural and military environment and stimulated by a study conducted by A. W. Jones enumerating <u>The Problems of Off-Road Mobility</u>[1*], the Advanced Research Projects Agency (ARPA) contracted with Cornell Aeronautical Laboratory, Inc. (CAL) in August 1966 for a six-month study to review the state of knowledge in off-road mobility and define a long-range program of research. The results of this study were published in March of 1967.[2]

In February of 1967 the contract was extended to include a second phase effort, and CAL then initiated research on a long-range program. This report presents a summary of the technical progress made during the period February to August, 1967.

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* See Section 9 for numbered references

The stated objectives of this ARPA-CAL Off-Road Mobility Research (ORMR) program are:

1) Acquisition of ORM knowledge and development of analysis, prediction and decision methodologies.

2) Organization of ORM knowledge and methods to facilitate use by members of the "mobility establishment".

In addition to pursuing specific research activities, CAL is also providing technical support to ARPA in its overall coordination and evaluation of off-road mobility research.

The ORMR program is systems oriented with the central effort comprising a system analysis group and four major technical discipline groups. Detailed technical studies of soil mechanics, vehicle-terrain interactions, human factors and environmental factors are fundamental to the goals of the overall program. These technical studies are necessary to help define quantitative inputs for mobility prediction and evalution and to permit competent assessment of on-going off-road mobility research. Data are being derived from exercise of detailed dynamics models, fundamental experiments, controlled vehicle tests, and detailed engineering analyses.

The research is being performed both by CAL and outside agencies under subcontract to CAL. Current subcontractors include Cornell University, Dow Chemical Co., and Wilson, Nuttall, Raimond Engineers, Inc.

It is anticipated that the above approach will lead to improved methods and techniques of predicting and evaluating the mobility of off-road vehicles. The methods or tools developed will facilitate:

1) Rational and systematic determination of military-vehicle characteristics and needs by high echelon vehicle planners, specifiers, selectors, and allocators, who must consider mobility trade-offs with all other military requirements.

2) Engineering and evaluation of hardware items by designers, fabricators and testers, leading to production vehicles that possess a required degree of structural integrity on exposure to specified off-road environments, and measured mobility performance in the field in agreement with design goals and predictions.

3) Efficient employment of those vehicles which have been made available to field commanders, drivers and other users in the field.

The ORMR program results fall into three categories of varying level of specificity. Category 1 information is primarily system oriented or broad scope in nature. The primary effort here is the development and application of a Phenomenological Model. This analytical tool is being developed by the system analysis activity through integration of the research efforts of the disciplinary groups. This model will afford comparative mobility evaluations of vehicles among as well as within classes. The model also will reveal critical mobility parameters and will permit vehicle design trade-off studies which will serve as inputs to further studies of cost-effectiveness.

The principal results obtained in Category 1 and discussed in the following sections relate to:

1) The determination that the mobility modeling effort best proceed at two levels;

a) Phenomenological (comprehensive evaluation model),

b) Vehicle System Dynamics (providing detailed inputs to a)).

2. The establishing of the general framework for the Phenomenological Model.

3. A preliminary methodology study using the Mobility Environment Research Study (MERS) Factor Family data.

4 Vehicle-environmental design adaptation studies using MERS data.

5. The systematic organization of information on current off-road mobility related research through DOD R and T resumes and other sources.

The items to be found in Category 2 are more detailed and pertain principally to vehicle system dynamics model(s), driving simulators, and/or a combination of these analytical/experimental tools. The vehicle system dynamics model(s) (VSDM) are being developed to supply inputs, e.g., tabular arrays or curves, to the Phenomenological Model. These models will be used within themselves to investigate general or specific problems of an ORM nature and to enlarge the existing data base. As the program progresses, it is expected that the off-road driving simulator will be coupled with the vehicle dynamics model(s) to provide a closed loop evaluation system.

The principal results obtained in Category 2 and discussed in subsequent sections relate to:

1) Review of current practice in mathematical modeling of vehicle-terrain systems.

2) The establishing of the framework for a vehicle-terrain dynamics model as an initial VSDM.

3) The determination that it is necessary to include the human in a closed loop vehicle system dynamics model to account realistically for driver-vehicle-terrain interaction.

4) Surveys of existing driver simulation facilities and techniques.

5) The development of specific techniques for handling environmental data, viz., automatic map reading, digitization, statistical processing and data retrieval.

6) The preparation of environmental maps providing a gross assessment of the severity of soft soil and stream crossing problems on a world-wide basis.

7) The usefulness of driver auxiliary information displays, as exemplified by a slip meter experiment being conducted.

Category 3 is comprised of fundamental information aimed at describing the basic mechanisms underlying the mobility process. The disciplinary groups produce this data as a portion of and as a supplement to the task of supplying the required inputs for the above described models. Results in soil mechanics, a quantitative definition of the factors involved in degraded driver visibility and new methods for defining terrain and vegetation are examples of what may be expected in this latter category.

Results obtained in Category 3 and discussed in subsequent sections relate to :

1) Fundamental soil mechanics and physics studies, including a brief study of a continuum mechanics approach treating soil as a ternary mixture.

2) The implementation of a visioplasticity approach to the problem of running gear-soil interaction.

3) A critical review of existing scale-model research and the recommendation that such work not be pursued for ORMR until a better understanding of the important physical factors of soils is achieved.

In addition to the above specific items, work of a continuing nature in the following areas is reported .

- Military vehicle requirement studies
- Vehicle case studies
- Vehicle structural and loading criteria
- Off-road mobility field test practices
- Test plans for driver visual field degradation experiments
- Concepts and methodology for analysis and application of environmental data

2. SYSTEMS STUDIES

In order to ensure that CAL ORMR activities maintain at all times a relevance and responsiveness to the framework of military application, we have directed appropriate efforts toward understanding; (1) the underlying military context of off-road operations, (2) recent off-road vehicle developmental and operational experience, and (3) specific information needs of the mobility community. These efforts may be viewed collectively as dealing with the informational interface between the off-road vehicle developer/user (practitioner) and the researcher/analyst, i.e., the inputs which each requires of the other. Progress in these areas is reported in Section 2.1.

The ability to quantitatively predict and evaluate vehicle performance, prior to its fabrication, or in a new and inaccessible environment, has been recognized from the outset as a major informational need of the off-road vehicle practitioner, and consequently as a goal of the ORMR program. To this end the conceptualization, development, and computer implementation of mathematical models of the mobility process are being pursued, as described in Section 2.2.

2.1 Informational Interface

2.1.1 Military Requirements

The established military requirements for transport of troops and materiel are the ultimate yardsticks by which vehicle mobility performance can be assessed. In view of our specific concern with ground contact vehicles only, we have concentrated initial efforts on requirements of the U.S. Army.

The approach, thus far, has been to:

1) Obtain and read pertinent U.S. Army planning documents and special studies,

2) Confer with U.S. Army Combat Development Command, Continental Army Command, and Department of Army staff personnel to identify documentation and achieve a personal orientation as to requirements, and

3) Review in detail the above information in order to identify key requirements.

Most of the work to date has been on (1) and (2). Specifically, draft copies of Concept Studies 70 [3], 75 [4], 80 [5] and Tactical Mobility requirements 1971-80 [6] have been given preliminary review; the latest versions have been requested. The Department of Army Combat Developments Objectives Guide,[7] a Department of Army Presentation on Tactical Vehicles (non-weapon)[8] and USACDC - U.S. Army Position Statements[9] also have been reviewed. Additionally, off-road mobility requirements of the Department of Army have been reviewed with the staff of that Headquarters and the U.S. Army Combat Development Command.

From our review of these and other information sources we expect to summarize vehicle materiel requirements in accordance with the following organization:

1) Composition of the complete family of off-road vehicles, including current vehicles and the time phased arrival of first and second generation replacement vehicles.

2) Technical performance characteristics for the above vehicles.

3) **Operational requirements, including**

   a. air transport air drop, fording and swimming capabilities, and

   b. environmental preparedness - artic, jungle and desert.

4) Organizational distribution of vehicle utilization - who will use vehicles designed for off-road mobility.

5) Auxiliary equipment to assist drivers in performing off-road operations; e.g., force assisting devices, swimming and fording aids, bridges, terrain sensors, and terrain displays.

6) Research impact of the above requirements.

2.1.2 Military Information Needs

We had previously categorized the military off-road mobility community by function, viz., high echelon planning, vehicle specification, design, development, fabrication, testing, evaluation, selection, allocation driver selection and training, field operational planning, and vehicle driving [2]. Further consideration of these processes has led us to identify critical needs for information and techniques which could be supplied by off-road mobility research, and which in fact are, in part, being pursued under this project. We briefly outline here some of the more salient items so that the reader can in subsequent sections associate specific applications with reported research tasks.

High Echelon Planning and Specification

1) * Standardized, quantitative measures of vehicle mobility performance.

2) * Standardized, quantitative framework for environmental description in terms of either measureable or already available data.

3) A comprehensive method for predicting gross relationships between achievable vehicle mobility performance and cost for various missions in broad classes of environmental areas.

4) Analytical aids for specifying improved vehicle families (capabilities and number of individual vehicles) to cover required spectrum of missions and geographical areas.

Design, Development, and Fabrication

1) Standardized, quantitative vehicle loading and reliability criteria.

2) Methods for predicting loads and failure statistics - and associated model for vehicle life cycle costs.

3) Improved expressions for soft soil tractive force as functions of vehicle design and soil parameters.

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* Information also basic to other functional categories.

4) Methods for predicting dynamic vehicle-driver-terrain interaction in uniform environments, - as specifically influenced by vehicle mechanical parameters (also components and subassemblies) and by vehicle-driver interface.

5) Rational process for adapting a vehicle design concept to a given statistical distribution of environments.

Testing

1) Standardized engineering and acceptance test practices, conforming to the elements of vehicle specifications and designed to be relevant to the spectrum of anticipated operational environments.

Evaluation, Selection and Allocation

1) Techniques for automatic processing and presentation of field test data.

2) Methods for both absolute and comparative evaluation of vehicle mobility performance in specific environments and specified distributions of those environments.

3) Methods for predicting the environmental performance envelope of a given vehicle.

4) Analytical techniques for inventory control.

Driver Selection and Training, Field Operational Planning, and Vehicle Driving

1) Improved understanding of desirable driver capabilities and the learning process.

2) Field information system for taking full advantage of environmental knowledge and vehicle capabilities in operational planning.

2.1.3 Vehicle Case Studies

A recent undertaking is an intensive survey of the developmental history and operationally demonstrated capabilities of selected vehicles in the Army's inventory. One purpose is to establish a realistic perspective of the off-road mobility performance of current military vehicles, e.g., frequencies at which various mobility problems are encountered and the nominal expenditures of time and effort to overcome impediments. This familiarity, once established and shared by other project personnel, will provide a basis for focusing on some of the more important research problems, i.e., those which relate to the vehicle performance factors where improvements are most badly needed. A second purpose is to highlight some of the practical constraints of vehicle design due to transportability limitations and the functional requirements for firepower, crew size, ballistic protection and human factors considerations. Still another motivation for these case studies is to search for correlations between engineering design practices, test data and user evaluation of performance. This type of search could be extended to uncover the factors which served as a basis for formulating the initial requirements for some of the vehicles to be included in the study.

The exact set of vehicles to be included in the case studies has not been established. Preferably it should include both vehicles which have won general user satisfaction and others which have led to general user

dissatisfaction as regards vehicular mobility. Similarly, representatives of both wheeled and tracked types would be desirable. However, existing wheeled types appear to offer very little information on operations in an off-road environment.

The M113 Armored Personnel Carrier, because of its abundance and current prominence in S. E. Asia is an obvious choice. Other likely tracked candidates are the M114 Reconnaissance and Scout Vehicle and one of the battle tanks - M48 or M60. All of the vehicles mentioned have one thing in common, namely a current U. S. Army program to design and produce an improved successor vehicle. The interest in these vehicles is therefore accentuated and continuing as progress is made in defining the successor vehicles which are required to offer some margin of improved off-road capability. In addition to these three types, the nature of information uncovered on self-propelled artillery, standard wheeled types up to the 2-1/2 ton, and the unconventional vehicles such as the Gamma Goat will be examined to determine if one or more of these should be added to the program.

Activity thus far has centered on establishing appropriate contacts in the key centers of information, and in the initial follow-ups to these contacts. Headquarters, U.S. Army Test & Evaluation Command (TECOM), has been visited to assess the extent and nature of information on vehicle test practices and test data. A review of the abundant number of test reports in the TECOM library has begun. Officials of TECOM concur in the objective of searching for meaningful correlations between design and performance, and imply that it is potentially a rewarding use of the performance test data they accumulate.

At Headquarters, U.S. Army Combat Developments Command, discussions have been held on user evaluations of vehicle equipment with officers recently reassigned from combat forces. This has led to obtaining several reports on the subject which are worthwhile prerequisites to further

and more extensive contacts with user agencies. Principal among the reports are: "Evaluation of U.S. Army Mechanized and Armor Combat Operations in Vietnam (U)", short title (MACOV),[10] and various ACTIV reports[11-19]. Also a few pertinent debriefing summaries of Vietnam returnees have been reviewed.

There has been some correspondence and discussions with vehicle manufacturers (specifically FMC Corp. and Chrysler Corp.) concerning their cooperation in the case study program. Participation of industry will be helpful in tracing the evolutionary aspects of the vehicle design; particularly those factors influencing off-road mobility. It will also (as evidenced by previous discussions with industry representatives) help in assembling specific information on the design constraints imposed by the military requirements other than mobility.

Information gathered to date is still largely qualitative. It is well-known that the M113 has enjoyed an acceptance in Vietnam, in contrast to the M114. Field test reports are being examined to see if the alleged differences in mobility could have been predicted, but it appears that the M114 went into the field with very little test history. Rather minor design differences in the two have been noted, but it would be premature to identify these as solely responsible for differences in user evaluation.

Another aspect of interest concerning the M113 in Vietnam is the vast number of field trials and expedients that have evolved. These include sand-bagged floors (to minimize mine damage), add-on bar armor, turret armament stations, and a remarkable number of water crossing techniques. The bar armor experiment was quickly abandoned because the added increment of width caused a substantial reduction in mobility in the Vietnam environment. The water crossing problem which is paramount in Vietnam, though not insurmountable, usually calls for considerable time and effort and the mutual assistance of two or more vehicles. The experimental M113 Vehicle Launch Bridge, similar to the 65 foot span M60 AVLB's,

is believed by many in the Army to be the most effective way of overcoming the narrow water obstacles.

From qualitative beginnings such as these mentioned, the environmental factors which adversely affect vehicular off-road capability can be identified, and sorted into basic problem areas. It is characteristic of many of these problem areas that their impact on distinct (though similar) vehicles - or on the same vehicle at different times - or on a given vehicle with varying auxiliary devices - will provide a means for discriminating among varying levels of performance. Where such distinctions can be made, the relevancy of certain specific aspects of design can be examined. A minimum set of such design features would include: ground clearance, horsepower loading, dimensions, buoyancy, drawbar pull, ground pressure, and track and suspension configurations.

The vehicle case study is proceeding according to schedule and will be fully documented on its completion.

2.2 Mobility Evaluation and Prediction

Off-road mobility performance of vehicles may be evaluated by mathematical modeling, by field testing of actual vehicles (or scale models thereof) or, in limited aspects, by theoretical analyses. Because of various limitations associated with the latter two approaches, e.g., expense, environmental control, repeatability, scaling validity, and system complexity, it is important to develop a comprehensive mathematical systems modeling capability. We have concluded that a sensible procedure within the ORMR program is to conduct modeling at two levels of detail, vis., (i) a Phenomenological Model (PM) which accepts regional environmental data and functional representation of vehicle performance in homogenous environments, and generates statistical measures of performance for the specified region; and (ii) Vehicle System Dynamics Models (VSDM) of varying sophistication which dynamically simulate the detailed

physical and human processes involved in operation of off-road vehicle systems. Thus the final process of vehicle mobility evaluation in a complex distribution of environments, as is associated with a given geographical region, would be divorced from the necessity of detailed reconstruction of the actual dynamic process in each elemental situation. Inputs to the PM will come from exercise of the VSDM, field testing, and analysis. Conversely, implementation of the PM will clarify what information needs to be provided and thereby guide in the development of detailed VSDM structure and emphases. The following paragraphs amplify our current position with respect to modeling and describe exploratory and methodological studies already undertaken.

2.2.1 Phenomenological Model

A general structure of the Phenomenological Model is indicated in Figure 2-1. Central to the model is the operation labeled "performance functions" in the diagram, which is basically structured around functional representations relating the performance of a vehicle to its physical characteristics and the local environment in which it is immersed. These are the representations which would be derived from detailed dynamics models, field test data, or direct engineering analysis.

Vehicle physical characteristics are a direct input. However, the complex pattern of environmental characteristics which describes a given region is subject to preprocessing of various kinds, a most important class of which is the derivation of environmental joint probability functions as induced by assumed spatial distributions. This is the significance of the output form p(E) from the environmental data processing box. Such output probability functions should also reflect pertinent military and mission considerations. It is planned, in addition, to account for spatial correlation in the environment by an appropriate means. As a possibility, it may be sufficient to replace the point density by a joint two-point probability function

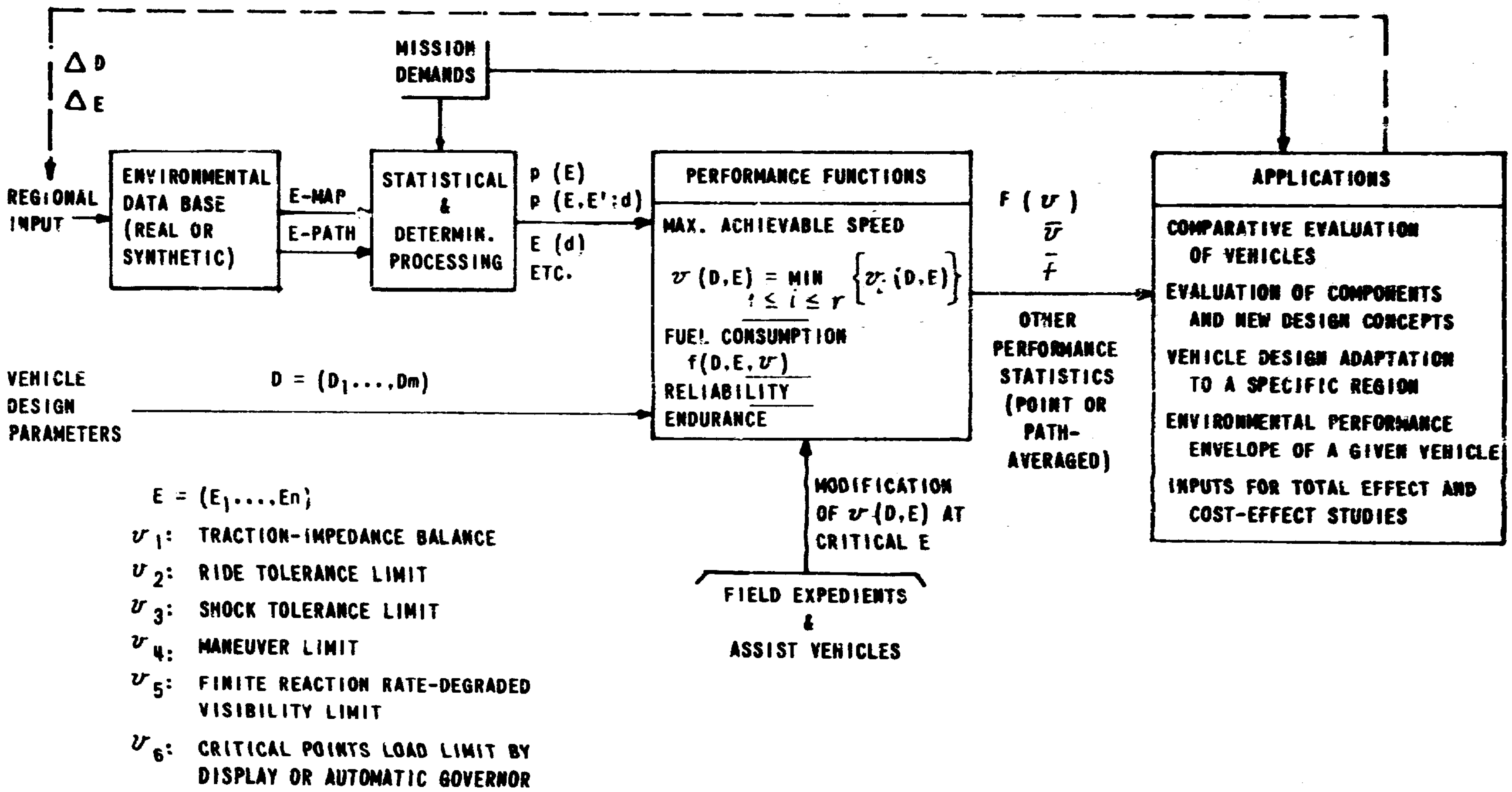


Figure 2-1 PHENOMENOLOGICAL MODEL

p(E;E';d), as suggested in the diagram, where E and E' are the environmental factors at two points separated by a distance d.

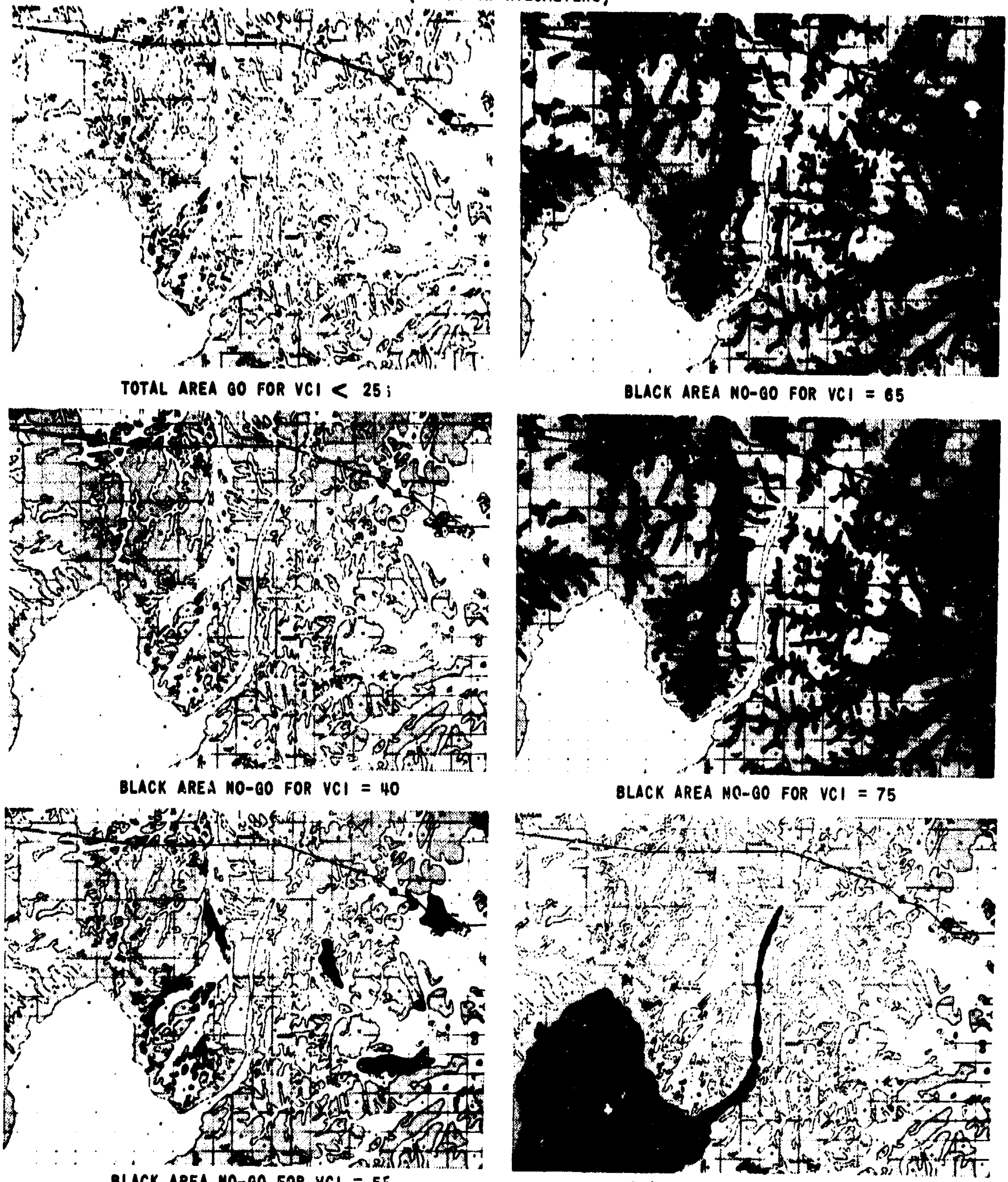
The output of the central block may be the cumulative probability distribution of achievable vehicle speed F(v); alternatively, only the expected value $\bar{v}$ or other special statistics on v, as appropriate to the evaluation process, may be generated. The same applies for other performance measures. Finally, the suggested concept of independence among $v_1, \ldots, v_r$ as individual-mechanism speed limits is perhaps a useful first approach, but data may indicate major interaction effects which will have to be taken into account.

Current efforts are directed towards defining the relationships between two major segments of the model, the environmental data base and the input performance functions, as well as establishing the specific functional relationships among the variables involved.

Two subsidiary tasks of some methodological import for phenomenological modeling will now be discussed briefly. The first was a modest effort completed at CAL; the second is a joint effort with Wilson, Nuttall, Raimond Engineers Inc. (WNRE) collaborating as subcontractors to CAL.

For the first study, an area about 18 x 24 km was chosen from a set of topographical maps of Thailand as terrain in which ground vehicles might be called upon to operate off-road. From MERS maps of the same area [20], soil softness was selected as the single factor to determine Go/No-Go for the first pilot study. Figure 2-2 clearly indicates areas accessible to vehicles in accordance with their vehicle cone index ratings (VCI). Some first attempts were also made to quantify statistical measures of how trafficable this area is as a function of VCI. The simplest index considered was % Go area; other more complicated, path-dependent indexes were also calculated. All the indexes were found to give comparable

(GRIDS IN KILOMETERS)



(FOR PRESENT PURPOSES THE GREY SHADINGS SHOWN SHOULD BE DISREGARDED)

Figure 2-2 GO/NO-GO MAPS FOR AN AREA OF THAILAND WITH TYPICAL SOIL-TRAFFICABILITY 4

measures for the area in question despite the fact that theoretically they could differ widely, e.g., in terrain with many large, disconnected Go regions.

The second study also deals with MERS Factor Family data (but more completely) and is ostensibly a program to demonstrate how detailed environmental data may be used for design adaptations of selected vehicles to a given region in terms of increased and better-connected Go areas. Moreover, it has also the purposes of developing automatic map reading and data processing techniques and of objectivizing and quantifying vehicle design-mobility performance relationships in current use.

The approach is an iterative vehicle design modification on the basis of Go/No-Go maps prepared by combined WNRE and CAL efforts. A first set was prepared manually but for subsequent iterations the map-making process has been almost completely computerized. Introduction of this computer procedure will produce two advantages, a reduction in the time required for map preparation, and perhaps more importantly, the development and validation of a procedure which can be incorporated into the framework of the Phenomenological Model. These studies will also provide some approximate engineering expressions which may be useful as the first functional representation inputs to the Phenomenological Model.

2.2.2 Vehicle System Dynamics Model

The construction at CAL of a succession of progressively more comprehensive Vehicle System Dynamics Models by a modular approach is envisioned, in order to achieve the capability to study many different situations.

Efforts are currently being pursued toward a VSDM as a combination of (1) a vehicle-terrain simulation (Section 3 of this report) and (2) a driving simulation (Section 4) permitting introduction of the human directly into the loop through appropriate representation of his environment in the

vehicle. This approach has been decided upon because present knowledge of human behavior does not allow adequate analytical representation of the driver as a controller and decision-maker in the complex situations encountered off-road. An important consequence is the requirement for a vehicle-terrain dynamics simulation model which operates in real time, indicating that the model will probably have to be hybrid, with most of the vehicle dynamics represented on our analog computers. As previously noted the VSDM's will be important data sources for generation of Phenomenological Model functional representations.

3. VEHICLE-TERRAIN INTERACTION

In the ORMR program, physical mobility has been broadly structured in such a way as to place in evidence three main interrelated elements -- the Driver, the Vehicle, and the Environment. In this context, the vehicle terrain interaction task of the ORMR project is concerned primarily with the Vehicle element. Interaction with the Environment has to date been limited to the problem of mathematically modeling the vehicle-terrain interface mechanics and to the separate problem of evaluating current soil trafficability theories.

The Vehicle-Terrain Interaction task has been subdivided into six problem areas: mathematical modeling of the vehicle-terrain system; evaluation of existing theories of soil trafficability; model-scale studies; field test practices; structural loading and reliability; and performance studies. The work under this task is expected to contribute to:(1) performance data appropriate for the exercising of the Phenomenological Model (discussed in Section 2. 2. 1), (2) solutions of special vehicle-terrain problems for application to vehicle design studies, (3) recommendations for improved vehicle testing procedures, and (4) recommendations for improved structural loading criteria. The performance data would be generated by the vehicle-terrain mathematical model (or models).

Progress has been made on three of the above problems. The work accomplished on mathematical modeling of the vehicle-terrain system -- in which emphasis is being placed on a vehicle dynamics model -- is described in Section 3. 1. Section 3. 2 describes the results of a critical review and evaluation of the state-of-the-art of scale-model techniques in predicting full-scale vehicle performance. In Section 3. 3, the status of vehicle structural loading and reliability studies is discussed.

3.1 Vehicle-Terrain Model Development

3.1.1 Model Requirements

The availability of an adequate vehicle-terrain computer model (or models) is recognized as an early need for the conduct of off-road mobility studies. Steps have been taken toward the development of a mathematical model of the vehicle-terrain interaction problem to satisfy this need. It is planned that the vehicle-terrain model will provide a capability for evaluating the performance of vehicles in a military mobility context. The nature of the model will depend, to a great extent, on: (1) the performance measures of interest, (2) the major factors that affect the variation of the measures, and (3) the manner in which the model will be exercised (computer, analytical, etc.).

Although overall mobility performance measures will have to be eventually defined, certain significant vehicle performance measures are now identifiable. For the general class of vehicle problems, these include: (1) vehicle speed and acceleration, (2) payload vibration and shock, (3) vehicle component loadings, (4) fuel consumption, (5) vehicle handling, and (6) payload capacity. Many factors can exert a significant influence on the performance measures. These include vehicle factors (such as number and size of wheels, vehicle weight, suspension characteristics, power plant and train), terrain factors (such as soil properties, ground roughness, grade variations, water distribution, vegetation), human factors (such as vibration tolerance and visibility), and mission type. An attempt must be made to identify the most important of these.

To assist in making decisions regarding model details and complexity, computer simulation requirements, etc., a survey was conducted of existing vehicle, terrain, and obstacle/environment models. Results from this survey are presented below in terms of the characteris-

tics that are considered most important. These have been broken down into vehicle, terrain, and data processing models.

3.1.2 Vehicle Models

The vehicle models are divisible into: (1) body-seat-running gear mechanics models, (2) performance models, and (3) component loadings models. Table 3-1 describes comparative properties of several body-seat-running gear mechanics models. The assumptions noted for each model are not exhaustive, but rather tend to be illustrative. Thus, for example, most of the models since Sattinger and Smith have assumed negligible velocity-product terms. Many of these models do not account for detailed seat mechanics, but can be adapted to include this aspect.

A list of surveyed performance models is presented in Table 3-2. The term "performance" in this case refers to the power train characteristics (as discussed in Reference 21).

Few mathematical models have been developed to investigate the dynamic loading of vehicle components. However, indications are that industry is using structural loading models,for example Reference 22 . In fact,adaptations of models such as those shown in Table 3-1 are probably being used for this purpose. One of the motivations for interest in these models is for the prediction of component and vehicle life. Some elaborate simulations are apparently being employed in the performance of these prediction studies [22].

3.1.3 Terrain Models

The terrain and obstacle/environment models can be categorized into: (1) rough terrain, (2) soft-soil, (3) vertical obstacle, and (4) water egress models. The operation of vehicles over a given terrain sample may sometimes have to deal with a combination of the above. For example,

Table 3-1

BODY, SEAT - RUNNING GEAR MECHANICS MODELS

STUDY	YEAR	DF	DIM.	VEHICLE MOD	SIM. TYPE	ASSUMPT.	OP. AMP.	INTEREST	VALID.	MOTION MONIT.	TERRAIN INPUTS	TYPE ANALYSIS	REMARKS	REFERENCE
SATTINGER & SMITH	60	7	3	M-151 4-WHEEL	ANALOG	SMALL ANGLES, YAW = SWAY = 0, CONSTANT SPEED	52	RIDE	YES	PITCH, BOUNCE, ROLL	DET. △ RDST. HARD, Z	TIME D	SUBJECTIVE COMPARISON OF TIME TRACES (PRODUCTS AND SQUARES OF ω AND INERTIA = 0). ASSUME WHEEL AS A DISC.	23
NEAL (ATAC)	61	7	2	TRACKED 5-DISC WHEELS/ SIDE	ANALOG	SMALL ANGLE, NO TRACK EFFECT, LINEAR SPRINGS, CONSTANT SPEED, SUSP. FRICT. NEG.	14 i**, 33 s	RIDE	NO	PITCH, BOUNCE	DET. HARD, Z	TIME D "STR. RESP."	"TYPICAL" VEHICLE DESCRIBED. NONLINEARITIES ENTER VIA VARIABLES: SHOCK ABSORBERS, BUMP STOPS, WHEEL SEPARATION. CONSTANT COEFFICIENTS.	49
PRASILOWSKI...(ATAC)	64	7	2	M-52 TRUCK + SEMITRAILER WHEELED	ANALOG	SMALL ANGLE, LINEAR SPRINGS, CONSTANT SPEED, SUSP. FRICT. NEG.	22 i, 75 s	RIDE	NO	PITCH, BOUNCE	DET. HARD, Z	TIME D	SAME AS ABOVE. DIGITAL COMP. TERRAIN INPUTS. DAMPING IN ARTICULATION JOINT. BUMP STOPS, WHEEL SEPARATION.	50
PRASILOWSKI...(ATAC)	65	10	2	XM-571 CARRIER AND TRAILER (TRACKED)	ANALOG	SMALL ANGLE, NO TRACK EFFECT, LINEAR SPRINGS, CONSTANT SPEED, SUSP. FRICT. NEG.	--	RIDE	NO	PITCH, BOUNCE	DET. HARD, Z	TIME G	SAME AS ABOVE. 4 WHEELS/BODY/SIDE USED 2 PACE 231 R COMPUTERS + BUMP STOPS. WHEEL SEPARATION.	51
NEAL	66	7	3	4-WHEELED SURVEY MODULE	ANALOG	SMALL ANGLE, LINEAR SPRINGS, CONSTANT SPEED, SUSP. FRICT. NEG.	14 i, 44 s	RIDE	NO	PITCH, BOUNCE, ROLL	DET. HARD, Z	TIME 0 TIME D	SPRING RATE PROGRAMMED USING MULTIPLIERS. (2 PACE COMP.?). TIRE MODELED AS SPRING, DAMPER, MASS SYSTEM.	52
[illegible]	64	3 & 2i*	3	TRACKED, n-WHEELS	DIGITAL	SMALL ANGLE, CONST. SPEED, NO TRACK EFFECT, ETC.	--	RIDE	NO	PITCH, BOUNCE, ROLL	DET. & RANDOM HARD, Z	TIME & FREQ. D	MATHEMATICAL EXPRESSIONS DEVELOPED FOR VEHICLE RESPONSE. DIGITAL PROGRAM "WRITTEN", BUT APPARENTLY NOT EXERCISED. T-?? TANK DATA PLANNED TO BE USED TO VERIFY THEORY.	53
SMITH (FMC)	65	3+(3/2)i + TIRE DEFL.	3	n-WHEELED (ALSO M-37)	DIGITAL	NONLINEAR SPRINGS WITH DISCONT., NONLINEAR SHOCKS, SMALL ANGLES	--	RIDE	YES	PITCH, BOUNCE, ROLL	DET. HARD, Z	TIME D	TIRE MODEL DEFORMS UPON IMPACT. "FOURIER SERIES CURVE-FITTING TECH. FOR TERRAIN"(?) CHANGE IN HORZ. SPEED BY ADD. EQU., LOW COST PER SOLUTION(?).	24,25
VAN DEUSEN Ia	65	7	3	M-37 4-WHEELED	ANALOG	SMALL ANGLE, NO BUMP STOPS	15 i, 13 s +10	RIDE	YES	PITCH, BOUNCE, ROLL	RANDOM HARD, Z	FREQ. ANAL.	APPROACH "USEFUL FOR ANALYZING BASIC SUSPENSION AND BODY RESONANCES." CAN ACCOMMODATE NONLINEARITIES. VALIDATION BY SUBJ. COMP. OF SPECTRA. TAPE RECORDED INPUTS.	27
VAN DEUSEN Ib	65	7	3	M-37 4-WHEELED	DIGITAL	SMALL ANGLE, NO NONLINEARITIES	--	RIDE	YES	PITCH, BOUNCE, ROLL	RANDOM HARD, Z	FREQ. GEN. ANAL.	USEFUL FOR HIGH-FREQ., LOW-DISPL. ANALYSIS WITH LARGE NUMBER OF D.F. MATRIX INVERSION IS INVOLVED.	27
VAN DEUSEN IIa	66	7	3	n-WHEELED	ANALOG	WHEEL SEPARATION, POINT CONTACT, YIELDING SURFACE, NO BUMP STOPS	6(n+1)i, 8+11n s +8	RIDE	NO	PITCH, BOUNCE, ROLL	INDEPENDENT RANDOM IN-PUTS TO BOTH SIDES, SOFT, Z	FREQ. ANAL. NO TIME D	FILTERED WHITE NOISE INPUTS. HYP. SOIL MODEL. SOLID AXLE AND INDEP. SUSP. VEHICLE MODELS. [illegible] CONCEPT IMPLEMENTED. NON-LINEAR COEFF. CAN BE ACCOMMODATED.	28,29,30

* i = NO. OF WHEELS
** i = INTEGRATORS
s = SUMMERS

Z = BOUNCE
X = SURGE

Table 3-1 (Cont.)

BODY, SEAT - RUNNING GEAR MECHANICS MODELS

STUDY	YEAR	DF	DIM.	VEHICLE MOD	SIM. TYPE	ASSUMPT.	OP. AMP.	INTEREST	VALID.	MOTION MONIT.	TERRAIN INPUTS	TYPE ANALYSIS	REMARKS	REFERENCE
VAN DEUSEN 11b	66	7	3	n-WHEELED	DIGITAL	NON-YIELDING SURF.	--	RIDE	NO	PITCH, BOUNCE, ROLL	RANDOM HARD, Z	FREQ. DOM. ANAL.	MATRIX INVERSION	20
McKENZIE-a (GM)	66	5	2	M-38 4x4-WHEELED	ANALOG	RIGID WHEELS, POINT CONTACT NO WHEEL SEP. + NO BUMP STOPS	28 i 85 s	MOBILITY	NO	PITCH, BOUNCE, (SURGE)	RANDOM SOFT, X, Z	TIME D	ALTHOUGH SURGE IS TAKEN INTO ACCOUNT IT IS NOT MONITORED. MECHANICS MODEL SEEMS TO DIFFER FROM USUAL. DYNAMICS ASSUMES HARD SURFACE. INDEP. SUSP., VALIDATION RECOMMENDATIONS.	31, 32
McKENZIE-b (GM)	66	8	2	M-116 TRACKED (5 BOG)	DIGITAL	5 ROAD WHEELS/ SIDE	--	MOBILITY	NO	PITCH, BOUNCE, SURGE	RANDOM SOFT, X, Z	TIME D	NO DAMPING FOR CENTER BOGIES. NONLINEAR COEFF. CAN BE ACCEPTED. SIMULATION TO REAL TIME RATIO = 200. CAN BE REDUCED TO 10. APPENDIX GIVES PROGRAM FOR CALC. SPECTRAL DENSITY. INTEG. OF DIFF. EQU.	31, 32
McHENRY (CAL)	67	11	3	PASSENGER 4-WHEEL	DIGITAL	SOLID AXLE REAR SUSP., INDEP. FRONT, POINT CONTACT	--	COLLISION STUDIES	PARTIAL	YAW, SWAY, ROLL, ETC.	DETERM. HARD	TIME D	INTEG. OF DIFF. EQU. TAKES 200 TIMES REAL TIME. USES 500 PT TERRAIN DESCRIPTION INPUT. CONSIDERING USING "VARIABLE SPRING" TIRE MODEL FOR OBSTACLES.	54
METCALF (CAL)	61	4/UNIT	2	ARTICULATED (3-UNIT)	ANALOG	BUMPS STOPS, CONST. RATE SPRINGS, LIN. VISCOUS DAMPERS, DISTR CONTACT TIRE WHEEL-SURFACE SEP.	25 i 60 s	RIDE	NO	PITCH, BOUNCE	ACTUAL PROFILE SAMPLE, Z	TIME D	ROLL OMITTED FOR SIMPLIF. TWO AXLE VEHICLE. RIDE BEHAVIOR MEASURED BY PROB. DISTRIB. OF VERTICAL ACCEL. ARTICULATION USES ABOUT 25% OF AMP.	55
CLARK (CAL) YM-1[illegible]-206	61	4	2	GENERIC TRACKED	NONE	-- --	--	RIDE	NO	-- --	PROFILE SAMPLE, Z	TIME D	TRACK TENSION TAKEN EXPLICITLY INTO ACCOUNT. EFFECT OF TRACK MASS CONCLUDED TO BE NEGLIGIBLE. USES IDLER SPRING. EQUATIONS SAID TO BE TOO COMPLEX FOR ANALOG COMP. TRACK MODEL BELIEVED MAINLY AFFECTED BY SEVERE PROFILES.	56
SEGEL (CAL)	65	5	3	PASSENGER 4-WHEEL	ANALOG	ROLL MOMENT FROM YAWING OF WHEELS IGNORED		LATERAL DYN	YES	SEVERAL	SMOOTH SURFACE, STEERING INPUTS	TIME D	ONLY LATERAL DYNAMICS ARE EXAMINED.	57
ASSEO (CAL) FOR 301	66	-	3	1963 BUICK	ANALOG	SMALL FRONT WHEEL DEFLECTIONS		LATERAL DYN	NONE	SEVERAL	CONSTANT	TIME D	TRANSIENT RESPONSE TO VARIOUS INPUTS.	58
PARKHILOVSKY	65	4	2	M-21 VOLGA PASSENGER	ANALOG	SPRINGS, TIRES, SHOCK ABSORBERS LINEAR		RIDE	YES	BOUNCE, PITCH	SAMPLE ROAD INPUT, Z	CORRELATION	INPUT EXPRESSED IN TERMS OF CORRELATION FUNCTION. R(o)e$^{-a/\sigma}$ cos $\beta\sigma$; PARAMETERS PRESCRIBED. OUTPUT CORRELATION FUNCTION CALCULATED. VALIDATION BY COMPARING BOUNCE CORRELATION FUNCTION.	59
WES	66		3	SEVERAL	DIGITAL		--	MOBILITY	NO	BOUNCE	DETERM.	EMPIRICAL	NO CAPABILITY FOR VEHICLE PARAMETER VARIATIONS.	39

* i = NO. OF WHEELS
** i = INTEGRATORS
s = SUMMERS

Z = BOUNCE
X = SURGE

Table 9-2

PERFORMANCE MODELS

STUDY	VEHICLE TYPE	SIMULATION	INPUTS	OUTPUTS	VALIDATION	COMPUTER TIME	REFERENCE
ARNO* RR-8 (JAN 1960)	TRACKED T113E1	DIGITAL (ELECTRO (DATA 204)	TX SPD - TX TORQUE - ENG SPD ROLLING RES - VEL VEHICLE WEIGHT PITCH DIAM SPROCKET FINAL DRIVE RATIO FINAL DRIVE EFFICIENCY COEFF OF FRICTION MAX TX SPEED EQUIV. MASS FACTOR TRACK INCREMENTAL INC IN SPEED SHIFT SPEEDS TRANSM RATIO GRADE	VELOCITY TIME DISTANCE TRANSM RPM ENGINE RPM SPROCKET TORQUE TRACTIVE EFFORT ROLLING RESISTANCE DRAW BAR PULL ACCELERATION GEAR RATIO	WITHIN 5%	11 MIN (18 MIN PRINTOUT)	60
ARNO* RR-9 (FEB 1960)	WHEELED XM151	DIGITAL	ENG. SPD - ENG TORQUE ROLLING RES - VEL TX EFFICIENCIES AND RATIOS GEAR SHIFT TIME TIRE SLIP (") VEHICLE WEIGHT ROLLING RADIUS REAR AXLE RATIO REAR AXLE EFFICIENCY COEFF OF FRICTION MAX ENGINE SPEED ENG SHIFT SPEED EQUIV MASS FOR WHEELS GRADE	SAME AS ABOVE EXCEPT WHEEL TORQUE REPLACES SPROCKET TORQUE	WITHIN 5%	20 MIN (12 MIN PRINTOUT)	61
MOTTIN* RR-32	TRACKED M60	DIGITAL	SIMILAR TO RR-8 (FOR MANUAL SHIFT- ENGINE RPM VS TORQUE FOR AUTOMATIC TX - TRANSM RPM VS TORQUE REQUIRED)	DRAW BAR PULL, VELOCITY, ROLLING RESISTANCE GEAR RATIO	WITHIN 5%	1 MIN (5 MIN PRINTOUT)	62
McKENSIE (GM) 1966	TRACKED M116	DIGITAL 7040/44	ENGINE SPD - HORSEPOWER CONV OUTPUT SPD - CONV TORQUE RATIO - CONV OUTPUT SPD CONV OUTPUT SPD - ENG SPD SPROCKET SPD - CONV OUTPUT SPD GEAR REDUCTION RATIOS ETC. FUEL RATE - ENG SPD	DRIVE TORQUE POWER OUTPUT REQUIREMENT FUEL CONSUMPTION	NO	--	31,32
McKENSIE (GM) 1966	WHEELED M38	ANALOG	ENG SPD - HORSEPOWER ENG SPD - TORQUE ENG SPD - WHEEL SPEED VELOCITY ERROR - THROTTLE POS VELOCITY ERROR - BRAKE TORQUE	SAME AS ABOVE	NO	--	31,32
ORDORICA (DANA) 1965	WHEELED	DIGITAL 1410	ENG. TORQUE, HORSEPOWER, K-FACTOR VS. RPM TORQUE RATIO VS SPEED RATIO TX RATIO AXLE RATIO ROLLING RADIUS VEHICLE WEIGHT	TRACTIVE EFFORT NET FORCE GRADEABILITY ACCELERATION DISTANCE TRAVELED	YES	30 SEC	65
WES 1965	WHEELED, TRACKED	DIGITAL	RATING CONE INDEX GEAR	SPEED DRAWBAR PULL MOTION RESISTANCE	NO	--	39
CHRYSLER, ET AL.	?	DIGITAL	?	?	?	--	-

*ASSUME HARD SOIL SURFACE

operation in soft-soil may limit the drawbar pull that may be available for overriding vegetation and/or attaining maximum speed.

Rough terrain models refer to hard-surface, generally irregular land profiles. Deterministic profiles comprised of, say, a series of triangular or rectangular blocks are employed sometimes to exemplify grossly rough terrain [23, 24, 25, 26]. Random profile representations are used by others [27, 28, 29, 30, 31, 33]. These models are usually of interest in ride performance studies. Table 3-3 shows the characteristics of some of these models.

Soft-soil models have been used in the determination of go/no-go conditions, and more generally, in the calculation of the residual drawbar pull that may be used for accelerating and/or overriding other obstacles once the various soil constants are known. Drawbar pull has been represented by Bekker[34] and others in terms of rolling resistance (via pressure-sinkage) and maximum tractive effort. Wills[35] and others have pointed out that the Reece form of the pressure-sinkage model seems to provide a better fit to the experimental data, for the soil samples employed. The Reece form is also considered to be more satisfactory from a theoretical standpoint than the Bekker model [36, 37].

The Waterways Experiment Station [38, 39, 40] has developed an empirical method for relating drawbar pull and motion resistance to soil values as measured by the cone penetrometer. The relationships obtained are based on extensive, laboratory-controlled conditions for frictionless and cohesionless soils.

The calculation of drawbar pull, etc., implies the use of the static behavior of soils. However, it is also of interest to know the dynamic behavior of soils, for example, in the determination of ride performance. Van Deusen, et al.[38] have developed a dynamic soil model which, however, is unvalidated. Schiffman[41] has discussed a theoretical model of soil dynamics for clay, whose validity is also not demonstrated.

Table 2-3

ROUGH TERRAIN MODELS

	PROFILE GENERATING MODEL	VEHICLE MODEL SIMULATION	VEHICLE INPUTS DEPEND ON	PROFILE TYPE
ARCHAMBAULT, ET AL. RR-44 1961	DIGITAL	ANALOG	NO. OF WHEELS (≤ 12) WHEEL SPACING	DETERM
VAN DEUSEN 1965, 1966	TAPE RECORDING OF TERRAIN SAMPLE	ANALOG	NO. OF WHEELS WHEEL SPACING	DETERM
VAN DEUSEN	ANALOG (SHAPED WHITE NOISE)	ANALOG	NO. OF WHEELS WHEEL SPACING	RANDOM
VAN DEUSEN	ANALYTIC SPECTRAL INPUT	DIGITAL		RANDOM
SMITH (FMC), WES	DIGITIZED PROFILE	DIGITAL	NO. OF WHEELS	DETERM
McKENZIE, ET AL. 1966	ANALOG (SHAPED WHITE NOISE)	ANALOG	SPEED	RANDOM
McKENZIE, ET AL. 1966	DIGITIZED SAMPLE OF TERRAIN PROFILE	DIGITAL		DETERM
BOGDANOFF, ET AL.	ANALYTICAL SPECTRAL INPUT	ANALYTICAL		RANDOM

The vertical obstacle models class can encompass grades, vertical walls and ditches, and vegetation. Grades can be handled by using a resistance type of calculation. Rettig and Bekker [46] have made scale model studies of wheeled vehicle performance over vertical walls and ditches. WES [39] employs an empirical relationship to estimate the work and tractive effort required to override obstacles, which appears to correlate favorably with measured values; included also are empirical relationships of the force required to override trees of different diameters. Bekker [43] has suggested that the inclusion of suspension systems may affect the inferences regarding obstacle performance.

Stream crossing provides special problems in mobility. The usual combination of steep slopes, soft soil, and water increases the likelihood of no-go conditions. Dugoff [44] is developing and exercising a model of stream egress by a wheeled vehicle. Baker [45] is conducting scale model tests of stream egress. Stoll [46] has indicated a correlation between the results of a simplified model of stream emergence and observed results in the field.

3.1.4 Data Processing Models

The mathematical model of a vehicle-terrain system typically requires the processing of the output variables. This treatment of the outputs can, clearly, put a burden on the recording and computing facilities employed for the model simulation. Among the types of processing typically employed in vehicle-terrain models are: strip chart recordings of transient responses of displacement, speed, and acceleration; computations of averages, maxima, variances, power spectra, and correlation functions. This listing provides some idea of the demands placed by such data processing.

3.1.5 Model Validation

The principal merit of the mathematical model in the vehicular field is its predictive property. It provides a convenient tool over which the engineer can usually exercise more control than on the real physical situation. However, the predictive ability of the model depends on how well it represents the true physical situation. To have confidence in the model predictions, the model must be validated. The process of validation involves the comparison of the model output with the corresponding measured output of the physical situation that it is supposed to represent.

The model validations that have been made typically involve a subjective comparison of the predicted and measured responses. The validation thus may involve looking at two transient responses and deciding, based on the discrepancy between the two responses, whether to accept the model as validated (this is typified by many of the models already cited). Resort is often made to "experience and engineering judgement" to explain away any differences between responses. It is rarely pointed out what degree of discrepancy would have been acceptable. A difficulty is that the comparison of functions, rather than point values, is usually involved [47, 48].

3.1.6 Model Development

Initial steps have been taken towards the development of an array of vehicle-terrain model types that might be implemented in a computer. It is expected that the vehicle-terrain models to be developed for this study will make integrated use of model types of the form discussed in the above sections. One model will be selected for the first implementation. No one model will be able to accommodate all of the problems that are of interest in mobility. Hence, the type of problem that may be handled by an initial model will be delimited. Thus, the initial vehicle dynamics model will probably be tailored around the straight-ahead ride and performance problem (handling problems, e.g., may have to be treated with a separate model).

Since speed of advance appears to be a key operational measure of mobility, it is desirable that the model have the capability of deriving such estimates.

The initial model will have to be descriptive enough to provide adequate information, but simple enough not to introduce excessive computational difficulties. As a minimum, it appears that the first model should account for four degrees of vehicular motion: bounce, surge, pitch, and roll. The model must be able to take into account drawbar pull and motion resistance (vs. environment and time), as well as the vehicle-terrain dynamics. Any possible simplifications in the model description will be determined, in part, by the type of terrain inputs and by the output measures of interest in the model application.

3.2 Survey of Vehicle Scale-Model Studies

The scale-model study was primarily concerned with the application of similitude principles to problems concerning vehicular soil/running-gear interaction mechanics, e.g., the prediction of prototype performance from scale-model test data. In addition, to obtain a broader understanding of the subject, it was necessary to include applications of dimensional analysis and similitude to more fundamental problems (e.g., plate sinkage) and to configurations having interaction with terrain other than at a soil/running-gear interface (e.g., earthmoving equipment).

A critique of the prior art was made based on the information contained in the available literature (some 60 sources were reviewed and are listed in the References[35, 36, 42, 43, 66-121]. A few reports may contain information of interest were not received at the time of this writing. It is believed, however, that the literature received and reviewed is sufficient to represent a realistic picture of the present state-of-the-art. Presumably, scale-model studies of vehicle/terrain interaction are currently being performed at various facilities. With few exceptions, information of this

type was not available so that the significance of such work could not be assessed. The details of this survey are discussed in a separate report to be issued shortly.

The more important scale-model studies reviewed are summarized briefly in Tables 3-4 and 3-5 -- the first dealing with studies directly related to vehicular scale-model soil/running gear interaction; the second covering related topics of interest.

The following observations were made from the survey of scale model literature.

Frictional vs Cohesive Soil

Substantial success has been achieved in correlating the performance (as usually indicated by drawbar pull and wheel sinkage) of pneumatic-tired vehicles and their moderately small (usually 4:1) scale-models in cohesionless soils [78, 83]. Laboratory model tests of rigid wheels and other configurations (e. g., plate sinkage and bulldozing) in dry sands have also shown evidence of model/prototype similitude[80, 86, 97, 100]. This sucess is apparently a consequence of the fact that purely frictional soil can be, in most cases, sufficiently characterized by one dimensionless parameter -- ϕ, eliminating the need to scale the soil in the model environment.

On the other hand, it can be generally stated that quantitative prediction of prototype performance from scale-model tests has been relatively unsuccessful in cohesive soils [91, 116]. As a result, quantitative model/prototype performance evaluation tests have been mainly confined to cohesionless soils -- largely limiting the usefulness of the scale-modeling approach since, according to Liston [116], these soils do not usually offer severe mobility problems.

TABLE 3.4 SOIL-RUNNING GEAR SCALE MODEL STUDIES

STUDY	YEAR	REF NO	SUBJECT	SOIL PARAMETERS	SIMILARITY TERMS	PERFORMANCE TERMS	EXPERIMENTS	SOIL TYPE	CONFIGURATIONS	VALIDATION	REMARKS
MARKWICK	44	67	DIMENSIONAL ANALYSIS OF TRACKED VEHICLE	[illegible] VISCOSITY			NONE	—	—		FIRST DIMENSIONAL ANALYSIS OF A SOIL/VEHICLE SYSTEM
NUTTALL STEVENS INST	49	68	EXPERIMENTAL SCALE MODEL STUDY	[illegible]	[illegible]	[illegible]	SOIL BIN	SANDY LOAM DRY SAND	RIGID WHEELS	[illegible]	FIRST EXPERIMENTAL STUDY OF SCALE MODELS IN SOIL LIMITED RESULTS
NUTTALL STEVENS INST	51	71	CONTINUATION OF PREVIOUS WORK	[illegible]	COHESIVE [illegible] SAND [illegible]	[illegible]	SOIL BIN	SANDY LOAM DRY SAND	RIGID WHEELS	[illegible]	RESULTS PARTIALLY INCONSISTANT WITH PREVIOUS WORK. INADEQUATE SOIL PARAMETER CONTROL
TRECOM SCALE MODEL PROGRAM	56 TO 61	72 76 77 78 83	MODEL-PROTOTYPE PERFORMANCE CORRELATION	[illegible]	[illegible]	[illegible]	FIELD TESTS	SAND SNOW	LCC MARSH BUGGY 1/4 SCALE MODELS	SUCCESSFUL CORRELATION OF MODEL AND PROTOTYPE PERFORMANCE	LOW SPEED, SIDE BY SIDE FIELD TESTS. NONCOHESIVE SOILS SOIL PROPERTIES MEASURED BY PLATE SINKAGE TECHNIQUE
HARRISON LLL	61	81	ANALYTICAL PERFORMANCE PREDICTION	[illegible]	NONE	[illegible]	SOIL BIN	DRY SAND FARM SOIL	CATERPILLER TRACTOR TMC FARM TRACTOR M 37 TRUCK AND 1/4 SCALE MODELS	ANALYSIS ACCURATE TO WITHIN 10%	BRAMBAR PULL PREDICTED ANALYTICALLY AND MEASURED EXPERIMENTALLY FOR MODEL AND PROTOTYPE VEHICLES
SPANSKI LLL	61	82	PROPOSAL FOR VEHICLE SCALE MODELING	[illegible]	[illegible]	—	NONE	—	—	NONE	PROPOSES A MODELING TECHNIQUE WHEREIN DP/W IS EQUATED BETWEEN MODEL AND PROTOTYPE USING EXPRESSION FOR DP
NICHOLSON & BOOKER CARDE	63	85	TRACKED VEHICLE PERFORMANCE	NONE	NONE	[illegible]	SOIL BIN	LOOSE SAND	SMALL SCALE TRACKED VEHICLE	QUALITATIVE EXTRAPOLATION TO FULL SIZE	SCALE MODEL e.g. LOCATION STUDY. ASSUMED MODEL PERFORMANCE IS COMPATIBLE WITH FULL SIZE BEHAVIOR. NO SCALING
VINCENT, HICKS, ET AL U OF MICHIGAN	63	86	DIMENSIONAL ANALYSIS OF WHEELS IN SOIL	[illegible]	[illegible]	[illegible]	SOIL BIN	SAND	RIGID WHEELS	EVIDENCE OF SIMILITUDE DEMONSTRATED	LOW SPEED, RIGID WHEEL TESTS. COHESIONLESS SOIL. DIMENSIONAL ANALYSIS PERFORMED USING BEKKER SOIL VALUES
COSTELLO & DEWHIRST	63	87	PERFORMANCE OF LUNAR VEHICLE	[illegible]	[illegible]	$\frac{DP}{W}$ [illegible]	SOIL BIN	1/4" GRAVEL	SMALL SCALE 6-WHEEL VEHICLE	NONE	CONCLUDED THAT DP/W IS NOT AFFECTED BY g FOR WHEELED VEHICLES IN COHESIONLESS SOIL
JINDRA GM	63	88	EVALUATION OF ELASTIC FRAME VEHICLE CONCEPT	[illegible]	NONE	DP, S [illegible]	SOIL BIN	LOAM, ADOBE	1/4 SCALE EFV	PREDICTED PERFORMANCE TRENDS VERIFIED BY MODEL TEST DATA	PERFORMANCE EVALUATION OF ELASTIC-FRAME VEHICLE CONCEPT. SCALE-MODEL TESTS PERFORMED AND ANALYTICAL PREDICTIONS MADE.
CLARK, SIMON & ROMA	64	91	PERFORMANCE IN COHESIVE SOILS	[illegible]	[illegible] OTHERS	$\frac{DP}{W}$, $\frac{Z}{d}$, S	FIELD TESTS	CLAY	MARSH BUGGY & 1/4 SCALE MODEL	LARGELY UNSUCCESSFUL	COHESIVE SOILS USED IN FIELD TESTS OF MODEL AND PROTOTYPE VEHICLE. NO SOIL SCALING. SINKAGE NOT SCALED CORRECTLY
SCHURING & EMORI GM	64	97	ANALYSIS OF SOIL DEFORMING PROCESSES	[illegible]	[illegible]	[illegible]	MISC.	SAND, CLAY	RECT PLATES, WHEELS AND WHOLE VEHICLES	EXPERIMENTAL DATA DRAWN UPON SUPPORT THEORY	RIGOROUS DIMENSIONAL AND SIMILITUDE APPROACH. IDEAL SOIL AND HIGH VELOCITY CASES ANALYZED. RESULTS COMPARED WITH DATA.
NUTTALL WES	65	38	PERFORMANCE DATA CONSOLIDATION	[illegible]	SEE TEXT	[illegible]	SOIL BIN & FIELD TESTS	SAND	PNEUMATIC TIRES	LABORATORY & FIELD DATA CORRELATED EMPIRICALLY	SIMILARITY NUMERIC DEVELOPED. PERFORMANCE DATA FROM LAB. AND FIELD TESTS CORRELATED FOR SAND
FREITAG WES	65	103 114	ANALYSIS OF PNEUMATIC TIRES IN SOFT SOILS	[illegible]	CLAY [illegible] SAND [illegible]	[illegible]	SOIL BIN & FIELD TESTS	SAND CLAY	PNEUMATIC TIRES	FAVORABLE CORRELATION OF LAB AND FIELD DATA	SCALING PARAMETERS DEVELOPED FROM DIMENSIONAL ANALYSIS AND LAB DATA. SOIL BIN & FIELD TESTS CORRELATED FOR SAND & CLAY.
SPONSLER NORTHROP	66	107	LUNAR VEHICLE SCALE-MODEL TESTS	[illegible]	NONE GIVEN	MISC.	SOIL BIN & FIELD TESTS	SAND	1/6 SCALE LUNAR ROVING VEHICLE	RESULTS CONSISTANT WITH EXISTING DATA	EVALUATION OF LUNAR VEHICLE CONFIGURATION. QUALITATIVE FULL-SIZE PREDICTION FROM SCALE MODEL TESTS
SCHURING GM	66	108	LUNAR PERFORMANCE SIMULATION	[illegible]	[illegible]	MISC.	NONE	—	—	NONE	FEASIBILITY STUDY OF SIMULATING LUNAR VEHICLE PERFORMANCE ON EARTH. SIMILITUDE TECHNIQUE DEVELOPED USING SCALE MODELS
DUGOFF & EHRLICH STEVENS INST	66	117	MODEL TESTS IN SUBMERGED SOILS	[illegible]	NONE	$\frac{DP}{W}$, Z, S	SOIL BIN	SUBMERGED SAND	1/6 SCALE M-76 AMPHIBIOUS VEHICLE	NONE	MODEL TRACKED VEHICLE TESTED IN SUBMERGED SOIL. NO SCALING UP. NO FULL-SIZE TESTS

*A List of Symbols follows

TABLE 35 RELATED SCALE MODEL STUDIES

STUDY	YEAR	REF NO	SUBJECT	SOIL PARAMETERS	SIMILARITY TERMS	PERFORMANCE TERMS	EXPERIMENTS	TERRAIN TYPE	CONFIGURATIONS	VALIDATION	REMARKS
LUNDGREN	57	73	SIMILITUDE IN SOIL MECHANICS	γ, c, κ * OTHERS	MISC	MISC	MISC	SAND, CLAY	MISC	DATA PRESENTED IN MOST CASES	APPLICATIONS OF DIMENSIONAL ANALYSIS AND SIMILITUDE TO BASIC SOIL MECHANICS PROBLEMS
BORG WARNER	57	75	AMPHIBIOUS VEHICLE RESEARCH	—	HYDRODYNAMIC	HYDRO	FIELD WATER TANK	WATER	SCALE MODEL AMPHIBIOUS VEHICLES	WATER TEST RESULTS CORRELATED	COMPARISON OF SCALE MODEL AND PROTOTYPE PERFORMANCE IS MADE, PRIMARILY IN WATER
RETTIG & BEKKER LLL	58	82	OBSTACLE PERFORMANCE OF WHEEL VEHICLES	NONE	NONE	OBSTACLE SIZE	LAB	HARD SURFACE	SMALL SCALE WHEELED VEHICLES	EXPERIMENTS SUPPORT THEORY	OBSTACLE CROSSING ABILITY OF WHEELED VEHICLES PREDICTED ANALYTICALLY. EXPERIMENTS PERFORMED WITH SMALL SCALE MODELS
COBB, CONRON & GENTRY CATERPILLER	61	79	EARTHMOVING EQUIPMENT PERFORMANCE EVALUATION	c, ϕ, γ, μ, A	NOT SHOWN	LOADS ETC	SOIL BIN	ARTIFICIAL SOIL	EARTH MOVING MACHINERY	QUALITATIVE EXTRAPOLATION TO FULL SIZE	EARTHMOVING TOOLS AND COMPONENTS EVALUATED QUALITATIVELY FROM SMALL SCALE TESTS. PERFORMANCE COMPARISON MADE FOR DESIGN PURPOSES
SCHURING BATTELLE INSTITUTE	64	97	SOIL/WHEEL INTERACTION	$c, \phi, k_\phi, k_c, n, \gamma$	MISC	MISC	SINKAGE TESTS	SAND, LOAM	VARIOUS PROBES	MORE DATA NEEDED	STUDY CONTAINS A DIMENSIONAL ANALYSIS OF PROBE SINKAGE. SOME EXPERIMENTAL DATA GIVEN
SULLIVAN –CATERPILLER	64	98	EARTHMOVING EQUIPMENT PERFORMANCE EVALUATION	c, ϕ, γ, μ	$\frac{F}{\gamma\ell^3}, \frac{c}{\gamma\ell}, \frac{v^2}{\ell g}, \frac{\ell}{\ell}, \phi, \mu$	LOADS ETC	SOIL BIN	ARTIFICIAL SOIL	SMALL SCALE SOIL SCRAPERS	QUALITATIVE EXTRAPOLATION TO FULL SIZE	DESCRIBES USEFULNESS OF EMPLOYING SCALE MODEL TECHNIQUES. NO QUANTITATIVE SCALING
LISTON & HEGEDUS LLL	64	100	DIMENSIONAL ANALYSIS OF PLATE SINKAGE	c, ϕ, γ	$\frac{M}{\rho}, \frac{c}{\rho}, \frac{c}{a\gamma}, \phi$	$\frac{z}{a}$	PLATE SINKAGE TESTS	SAND, SNOW	RECTANGULAR & CIRCULAR PLATES	CORRELATION OF EXPERIMENTAL DATA ACHIEVED	PRESSURE-SINKAGE RELATION DEVELOPED FOR FRICTIONAL SOIL BY DIMENSIONAL ANALYSIS. COMPARED WITH BEKKER EQ. DATA
NEUMEYER & JONES CHRYSLER	65	106	MARSH SCREW SCALE MODEL TESTS	NONE	HYDRODYNAMIC	HYDRO	FIELD TESTS	SAND, MUD, OTHER	1/6-SCALE MODEL OF MARSH SCREW	ACCEPTABLE CORRELATION WITH FULL SIZE WATER TEST DATA	SCALE MODEL PERFORMANCE TESTS IN VARIOUS MEDIA. ONLY RESULTS OF WATER TESTS SCALED UP
REAVES, COOPER & KUMMER	66	111	MODEL STUDY OF SOIL/CHISEL SYSTEM	c, ϕ, ρ, A, PR	$V/\sqrt{g\ell}$, $c'/\rho g\ell$, $PR/\rho g\ell$	$\frac{F}{\rho g\ell^3}$	SOIL BIN	MISC	VARIOUS MODEL SOIL CHISELS	MODEL DISTORTION CORRECTED EMPIRICALLY	FORCES EXERTED ON A VERTICAL CHISEL BY SOIL IS PREDICTED BY SMALL-SCALE TESTS THROUGH APPLICATION OF MODEL THEORY.
SCHAFER, BOCKHOP & LOVELY	66	112	MODEL STUDY OF TILLAGE IMPLEMENTS	γ, M, OTHERS	$\frac{V^2}{g\ell}, M$, OTHERS	$\frac{F}{\gamma\ell^3}$	SOIL BIN	LOAMS	MODEL AND PROTOTYPE TILLAGE DISCS	MORE DATA NEEDED	A METHOD IS OUTLINED WHICH UTILIZES SCALE-MODEL TESTS TO EVALUATE TILLAGE IMPLEMENTS
LARSON, LOVELY & BOCKHOP	66	113	SCALE MODEL PLOW STUDY	c, ϕ, γ, μ, A	$\frac{V^2}{g\ell}, \frac{c}{\gamma\ell}, \frac{A}{\gamma\ell}, \phi, \mu$	$\frac{F}{\gamma\ell^3}$	SOIL BIN	MISC	MODEL MOLD-BOARD PLOWS	GOOD AGREEMENT BETWEEN THEORY AND EXPERIMENT	SIMILITUDE TECHNIQUES ARE APPLIED TO A PLOW/SOIL SYSTEM. DISTORTION FACTORS APPLIED
WILLS	66	35	PLATE SINKAGE STUDY	c, ϕ, γ	$\frac{c}{\gamma\ell}, \phi$	$\frac{z}{\ell}, \frac{F}{\gamma\ell^3}$	PLATE SINKAGE TESTS	SAND, CLAY	RECTANGULAR PLATES	SIMILARITY METHOD ACCURATE FOR LOW SINKAGE	PLATE SINKAGE IN VARIOUS SOILS IS ANALYZED USING SIMILITUDE, FUNDAMENTAL, AND EMPIRICAL METHODS. COMPARED WITH DATA
FIRTH	67	120	STUDY OF SOIL RESISTANCE TO COMPACTION	c, ϕ, γ	MISC	MISC.	MISC.	MISC	MISC	THEORY IN AGREEMENT WITH EXPERIMENTAL DATA SHOWN	A GENERAL SINKAGE EQUATION IS DEVELOPED. REDUCES TO EXISTING EQUATIONS. FORMULA FOR ROLLING RESISTANCE DERIVED

* A List of Symbols follows

LIST OF SYMBOLS FOR TABLES 3-4 AND 3-5

Symbol	Description	Dimension
a	Perimeter of plate	L
A	Soil adhesion	$ML^{-1}T^{-2}$
b	Tire width	L
c	Cohesion, Coulomb	$ML^{-1}T^{-2}$
c_s	Effective structural cohesion	$ML^{-1}T^{-2}$
c_t	Post-collapse structural cohesion	$ML^{-1}T^{-2}$
CI	WES Cone Index	$ML^{-1}T^{-2}$
d	Depth of soil or cutting depth	L
DP	Drawbar pull	MLT^{-2}
E	Young's modulus	$ML^{-1}T^{-2}$
f	Coefficient of friction	-
F	Force, general	MLT^{-2}
g	Gravitational acceleration	LT^{-2}
G	Average rate of increase of CI with depth	$ML^{-2}T^{-2}$
h	Tire section height	L
k_ϕ	Frictional sinkage modulus, Bekker	$ML^{-n-1}T^{-2}$
k_c	Cohesive sinkage modulus, Bekker	$ML^{-n}T^{-2}$
K	Modulus of compressibility	$ML^{-1}T^{-2}$
l	Characteristics length	L
M	Moisture content	-
n	Sinkage exponent, Bekker	-

Symbol	Description	Dimension
p	Pressure	$ML^{-1}T^{-2}$
PR	Resistance to 30° cone penetrometer	$ML^{-1}T^{-2}$
Q	Wheel torque	$ML^{2}T^{-2}$
r	Soil grain size	L
R	Total rolling resistance	MLT^{-2}
s	Slip ratio	-
t	Time interval	T
V	Speed	LT^{-1}
W	Weight or load	MLT^{-2}
Z	Sinkage	L
α	Aspect ratio	-
γ	Soil specific weight	$ML^{-2}T^{-2}$
δ	Tire deflection	L
λ	Geometric scale ratio	-
η	Soil viscosity	$ML^{-1}T^{-1}$
μ	Interface friction coefficient	-
ρ	Soil mass density	ML^{-3}
ϕ	Angle of internal friction, Coulomb	-
ω	Angular velocity	T^{-1}

Correlation of Empirical Data

Studies mainly concerned with correlation of empirical performance data taken from field and soil bin tests of pneumatic tires in sand and clay (no composite soils) have recently been made [38, 103] based on dimensional considerations. In these particular investigations, pertinent (usually dimensionless) terms or numerics are developed from system parameters judged to be important and then manipulated and/or altered so that model and prototype performance data "collapse" when plotted as a function of the evolved similarity term(s). These studies presumably allow predictions to be made of field performance of certain vehicles from representative soil bin tests. The WES cone penetrometer has been found to be adequate as the soil measurement instrument in these (mainly WES) dimensionally oriented studies of tire performance.

Tracked vs Wheeled Vehicles

There is a dearth of information in the literature surveyed regarding quantitative experimental scale-model investigations of tracked vehicles (based on principles of dimensional analysis and similitude), relative to the more numerous studies of wheeled (mainly pneumatic-tired) vehicles.

Composite Soils

A relatively insignificant amount of scale-model research using composite soil (e.g., loam) has been reported in the literature reviewed. The rigorous dimensional analysis/similitude approach appears to be difficult to apply in practice to such soil (joint frictional and cohesive properties) since multiple soil parameters must be properly scaled for exact similitude to

exist. It appears that stable, reproducible, and realistic artificial soil having independently controllable properties (permitting systematic soil scaling) must be developed for accurate prediction of prototype performance in composite soils from scale-model tests.

Soil Parameters

The literature surveyed reflects considerable controversy regarding the choice of meaningful soil value parameters. The Coulomb parameters (c, ϕ), Bekker soil values (k_ϕ , k_c , n), combinations of Coulomb and Bekker parameters, and such numerics as the WES Cone Index have all been employed in studies dealing with soil/vehicle interaction. In fact, a validated and universally accepted system of soil values is still lacking. It appears that a comprehensive study is needed, preferably on a fundamental soil mechanics level, to evaluate the adequacy of the soil parameters now in use and, if necessary and feasible, develop more meaningful and fundamentally valid soil parameters (see, e. g., [115]). It is conceded, however, since natural soil is largely a nonhomogeneous, anisotropic, and three-phase (solid--liquid--gas) medium, that the development of such basic soil parameters would be a formidable task.

Qualitative Scaling

Scale-model research appears to be very useful in situations where a qualitative evaluation of new concepts or a comparative investigation of design changes is desired [85, 107, 117]. Applications of this nature are based on the plausible assumption that gross performance trends exhibited in small-scale tests would also be present in full-size behavior. No quantitative scaling, employing a formal dimensional analysis, is usually attempted.

Such qualitative evaluation techniques have been successfully utilized in model studies of earthmoving equipment and other specialized vehicular configurations. Valuable new concepts such as the space track, articulated vehicles, and vehicles propelled by threaded cylinders have been tried out and substantially improved in design by means of (basically qualitative) scale-model experimentation[102, 118].

Prediction of Prototype Performance

Prototype performance (drawbar pull, sinkage, etc.) can be directly predicted from the results of small-scale model tests if conditions of similitude between the full-scale and model configurations are satisfied. Off-road terrain (soil, in particular) is, in general, very difficult to scale, however, and in most cases such terrain scaling is not attempted -- resulting in distortion of model/prototype similarity. This distortion can sometimes be accounted for and compensations made, but much more research is needed if practical techniques for evaluating distortion are to be developed for routine use.

The lack of a universally accepted and completely proven set of descriptive soil parameters also detracts from the usefulness of the scale-model approach and may in fact be at the root of the problem.

For the above reasons, it is recommended that no scale-model work of this nature be undertaken in the Vehicle-Terrain Interaction Task of the CAL ORMR program during the present Phase II effort. There may be justification for initiating such work later if the soil mechanics studies offer a promise of achieving a broader based theoretical foundation in soil behavior than now exists.

Validation of Mathematical Model

Scale-model test data have been used to validate (or at least tend to verify) mathematical models of ground-supported (and other) vehicle performance [81, 88]. For this type of application it is usually not necessary for the scale-model and prototype environment to be exactly similar, in a rigorous dimensional analysis/similitude sense, but only to possess the same general vehicle/terrain interaction mechanism, as characterized by the mathematical equations under examination. Thus, complete quantitative soil property scaling is usually not necessary in a scale-model environment to be used for validation purposes. It is assumed only that the mathematical model, if it describes the vehicle/terrain interaction mechanism adequately, is equally applicable to any size (mechanically similar) configuration -- usually justifying an experimental scale-model validation approach if it is advantageous (technically, economically, or otherwise) and desirable.

Since the current ORMR program includes the development of a validated vehicle/terrain mathematical model, it is recommended that validation techniques utilizing scale-model tests (in lieu of full-scale tests) be taken into consideration if and when validation tests are required, and, if desirable, a further study be made to justify the feasibility of such an approach.

3.3 Vehicle Structural Loading and Reliability Studies

In Reference 2 it is noted that no mandatory quantitative structural loading criteria exist for military vehicles. Proof of structural integrity is postponed until each vehicle, or its components, can be tested as hardware. It is argued that time and money can be saved and a more reliable vehicle will result if quantitative structural and reliability criteria are established

and used as a basis for evaluation before the vehicle is built. It is the overall objective of the study outlined herein to establish such evaluation measures.

The particular purposes of this study are threefold:

a) To obtain and record information on existing criteria, specifications, techniques, etc., used for the structural design and the reliability determination of off-road vehicles and their major components.

b) To initiate the definition of consistent, quantitative structural criteria designated for use by the military and industry during the selection, design, test and evaluation phases of off-road vehicle procurement.

c) To determine the need for a rational methodology for predicting vehicle reliability and life, and, if so needed, to initiate definition of such a methodology.

In the main, only the first of the above objectives has been pursued to date. Published literature has been obtained and reviewed and pertinent loading and reliability information has been extracted therefrom. The design departments of nearly a dozen off-road vehicle manufacturers have been contacted to obtain data on their design practices and in-house criteria for loading and reliability.

While this survey is still incomplete, ; tentative conclusions and observations can be made at this time, namely:

Concerning Loading:

(a) Designers and manufacturers of off-road vehicles have developed and made use of in-house static and dynamic structural criteria for the design of all major vehicle components. All of the manufacturers contacted to date have indicated that the details of their criteria are considered to be "proprietary" and not releasable to "outsiders". As a result, only a meager amount of detailed information has been forthcoming; dialogues with industry have been limited to discussions of design philosophy and methodology. Efforts are continuing to obtain more detailed criteria.

(b) The early construction and operation of an engineering test rig is one of the more common methods used by industry (and the military) for checking out vehicle feasibility, performance and (in some instances) structural integrity. Very often, test rig materials, component morphology and methods of construction are not representative of their production vehicle counterparts, the test rig being assembled from existing parts and available materials. Hence, the failure of a test rig part may not validly portend the failure of a similar production part. Proof of structural integrity, therefore, is often never formally provided to the purchaser of the vehicle; it is implied informally by the non-failure of the production vehicle (a very positive method of proof-- when it works).

(c) In addition to the test rig and in-house criteria, industry sometimes conducts laboratory tests to prove the integrity of structural components. These tests, however,

appear to be limited primarily to those parts that have failed on the test rig or on similar production vehicles. The lab tests are usually designed to correct failure and not to prevent or anticipate failure. In fairness to industry, it must be noted that the vehicle purchaser (i. e. the military) does not require such prior proof of structural integrity.

(d) Those vehicle manufacturers and designers who were contacted personally were asked what their attitudes might be toward a government imposed set of structural criteria. All reactions were guarded and cautious. It appears that, because the larger companies are now doing extensive analyses in-house, they would not be adversely affected by such mandatory specifications. The individual designer, who has neither the staff nor the funds to completely document his design (from a structural standpoint), may be hard pressed to comply with such mandatory criteria. One compensating factor is that the large manufacturer builds vehicles in quantity (for which more extensive documentation may be required), while the individual designer concentrates on pilot type vehicles (for which minimum documentation may be required).

Concerning Reliability:

(e) In its definition of vehicle requirements (e.g., in a QMR), the government demands that the vehicle be reliable (i. e., remain intact and continue to operate for a specified number of miles or hours). However, government procurement practice is such that it usually purchases the vehicle that has the lowest initial cost.

These two practices are often in conflict. To bid this low initial cost, the vehicle manufacturer reduces or eliminates the more costly materials, manufacturing processes, inspection procedures and tests that are necessary to insure high reliability. Furthermore, it has been stated [122] that the cost of maintenance and repair during a vehicles entire lifetime is often ten or more times its initial cost. Hence, in purchasing the lowest initial-cost vehicle, the government may inadvertently obtain a less reliable one. One suggested cure for the dilemma is to have the purchaser demand (by written specification) prior proof of vehicle reliability. Hence, all manufacturers bidding on a vehicle will be forced to add the reliability cost to the initial vehicle cost; hopefully, a more reliable vehicle will result.

The literature search and discussions with industry accomplished to date serve to reinforce the major argument of this substudy, namely, that:

Time and money can be saved and a more reliable vehicle will result if quantitative structural and reliability criteria are established and used as a basis for evaluation before the vehicle is built.

4. HUMAN FACTORS

In introducing the human into the physical mobility structure of off-road vehicles, the initial endeavor was directed at mathematically representing the human in the vehicle-terrain-driver model. It was recognized at the outset, however, that it would be necessary to rely upon empirical means for the acquisition of a suitable quantitative understanding of human performance. The data gathering methods which have been chosen as suitable are;

a) observing and interviewing operational personnel and trying out the tasks where possible,

b) testing, in which military vehicles are used to gather data under field conditions, and

c) conducting simulations wherein data can be gathered inexpensively under controlled laboratory conditions.

These are not meant to be isolated techniques, but rather should complement one another. The first technique, using observing, interviewing and participation procedures, is employed when experience of operational personnel can be used to define, substantiate and narrow the problem. For example, it was felt that we knew too little about decision-making problems of operational personnel, and that technique was used with that problem. Field testing will be used to establish realistic base-line performance. All of our future studies will be run to establish this type of baseline. Lastly, simulation studies will be used for intensive and extensive investigation of various parameters.

It is pointed out that the position is now taken to rely heavily on the introduction of the driving simulator into the loop with the vehicle-terrain model as an alternative to representing the driver by mathematical means. This technique has been proven successful in other applications and lends itself readily to the ORM problem.

The following paragraphs describe our recent efforts in the human factors area.

4.1 Driver/Commander Decision Making

Any comprehensive model of off-road vehicle performance must include some representation of the decision-making processes carried out by the humans involved in the task. Work on the decision-making phase of the ORMR project to date has consisted essentially of defining the problem or problems. What are the decisions that must be made while operating a vehicle in an off-road environment? What are the factors that are most relevant to these decisions, and in what way do these factors influence such decisions? Recent efforts have been directed toward finding answers to these questions.

Our first step in collecting information and data on the decision-making task was to observe vehicles operating in the off-road environment. Two visits, one to Camp Drum where the 27th Armored Division of the New York National Guard was stationed and the other to the TECOM organization located at Fort Knox, provided an opportunity for such observations. On both occasions our efforts included actual experience in operating off-road vehicles, discussions with people responsible for commanding armored units, discussions with people responsible for training crew personnel, and discussions with experienced crew personnel. The vehicles involved in these visits and discussions were the M113 armored personnel carrier, the M48 tank, the M60 tank, and the M551 armored assault vehicle. Our

personal driving experiences included operating the vehicle in a variety of off-road conditions, but not including swimming operations.

We also had an opportunity to observe extensive training exercises at Camp Drum wherein many M113's entered, swam and exited from a stream. The current in the stream was approximately 5 mph. One clear-cut conclusion was that drivers require extensive training in this type of task. The longer lag in vehicle response as compared to driving on land resulted in considerable difficulty in control.

From these experiences and the discussions with operational personnel, it has become apparent that the vehicle commander is the key figure in most decisions concerning vehicle operation. This conclusion, of course, does not apply to the molecular control decisions that would be carried out by the driver; that is, decisions regarding steering wheel deflection and accelerator or brake pedal pressures. The conclusion does, however, seem to hold for most decision-making processes that might be considered crucial to the operation of the vehicle. For example, the commander would certainly be involved in decisions regarding route selection and speed.

A second conclusion based upon these experiences is that, except for difficult or unusual terrain situations, the decisons regarding route selection, speed, etc. are fairly routine. That is, they are covered by standard operating procedures and do not appear to present any problems for modeling. Perhaps another way of thinking about this particular point is to suggest that, except for unusual or difficult situations, a small percentage of the commander's efforts need be devoted to making these types of decisions. Under conditions where the terrain is less familiar or more difficult, however, the commander will undoubtedly be required to devote a greater amount of attention to decision-making activities. For this reason, the difficult and unusual situations would appear to be most fruitful for further study.

A next logical step in studying the decision-making processes would then be to select a few difficult situations for investigation. Examples of such situations include exiting streams, negotiating ditches, negotiating wooded areas, and negotiating impediments (rocks, etc.).

4.2 Visual Degradation Effects on Driver Performance

The driver of an off-road vehicle relies primarily on his own or his commander's visual inputs for information on the intended path of travel. When something acts to degrade the transmission of such information to the driver, his performance and thus system performance often is adversely affected. Fog, rain, snow, dust, and night conditions are common sources of visual degradation. Natural objects, such as trees and brush, also can mask or block important terrain features and restrict the forward view of the path to an extent that it significantly influences driver performance. Design features of the vehicles themselves often contribute to the degradation. A severely restricted field of view, a seating position that results in a relatively low eye height, inadequate vibration damping, etc., are often characteristic features of vehicles and all interfere with the visual perception of the outside world.

The problems of seeing under fog, rain, snow, and dust conditions have received much less attention than has the night vision problem. In addition to the loss in visual information and the distortions that occur under these conditions, the concomitant factors of mud, slippery snow and ice, etc., that often occur in these situations must also be considered since they obviously will affect system performance and thus may alter the significance of many of the visual cues.

An extremely important question in regard to the effects of visual degradation relates to the way in which the information is to be used. In some cases, the driver must operate solely on the basis of what he can see from his vehicle. In such cases, he must be extremely alert to possible

obstacles in his proposed path that might interfere with the expeditious completion of his mission. In other cases, through the use of maps, briefings, or perhaps through previous experience with the route, he may possess considerable advance information about the proposed route and thus can concentrate on looking primarily for expected landmarks and obstacles.

We have been developing an information base through an intensive literature search, talks with drivers, crew personnel and research personnel engaged in relevant research, preparatory to the formulation of a program of further investigation. The aims of this program are:

1) To organize an adequate body of knowledge for use in off-road vehicle system studies concerning the basic capabilities of humans to detect and recognize objects important to off-road travel under viewing conditions likely to be encountered in the field. These include night, fog, rain and snow conditions. Some work of this nature currently is being conducted at facilities such as the Institute for Research in Vision, of the Ohio State University, the Night Vision Laboratory at Fort Belvoir, Virginia, and the Human Engineering Laboratory at Aberdeen Proving Grounds. These and other efforts still provide only a partial coverage of the area and additional research of this type aimed specifically at the ORM problem is required.

2) To determine the effects on driver performance of obscuration of portions of the field of view because of trees, brush, vehicle restrictions, etc. Fog, rain and other such conditions also can induce an effective restriction of the field of view. Primary interest at this time is with obscuration of the forward field of view. Current experimental plans call for systematic variation

of the forward sight distance under various driving conditions as, for example, those encountered in driving a straight path, a slightly winding path, and a very winding path. Previous research indicates that forward sight distance is a critical factor in highway driving performance. It is our intent to extend this research to include off-road performance.

3) To investigate the effects of driver expectancies and experience (or previous information) on driver performance. Emphasis here will be on the systematic variation of driver expectancies and experience to determine the effects on the information requirements of the driver. This will be accomplished by putting drivers in situations where: 1) they receive little or no information as to what they might encounter along a directed route of travel, 2) they receive only partial information about what to expect along the route, and 3) they are thoroughly briefed and perhaps even familiarized with the route. Certain of the critical visual inputs also will be systematically varied. This will enable us to obtain further quantitative information regarding the effects on performance of the changes in visual information requirements that are expected to occur under the various experimental conditions.

4.3 Increasing Mobility Through Auxiliary Information Displays

There is reason to believe that increased performance would be obtained from an off-road vehicle driver if additional systems and environmental information were made available to him. This information can be regarded as being derived from three sources: the vehicle, the environment and the vehicle-soil interface. For example, one may consider the vehicle

and its limitations. There are many reports indicating that the driver, with proper restraints, can tolerate much greater accelerations than can the vehicle. It is clear that if the accelerations being imposed at critical points of the vehicle were presented to the driver in some manner, the driver might maintain lower maintenance rates by using this information to adjust his speed.

For another example, one may consider the limitations imposed by environmental factors. In particular, there can be no question that mobility could be increased at night if the driver were given some sort of visual aid to allow him to see as well as he can during daylight. A third example of potentially useful information which could be made available to the driver is a measure of the slip taking place between the running gear and the soil. This information might help prevent vehicles from becoming mired by aiding the driver to employ better procedures for maintaining traction.

It appears then, from at least three considerations (vehicle factors, environmental factors, and soil factors) that there is a possibility of improving performance by supplying the driver with information which is not now available to him. This performance improvement may be obtained through the use of visual aids or through visual or other types of displays that present necessary critical information in a literal or coded form easily interpreted by the driver. To this end, we have selected for study the slip-indicating device, mentioned above. We are currently conducting an experiment to evaluate the benefits to the driver of this added information.

The slipmeter under evaluation is a device which displays a specific function of the Actual Forward Velocity (AFV), as indicated by a "fifth-wheel" device, and Running Gear Velocity (RGV), which is the speed shown on a speedometer. Slip is defined by the expression $1 - \frac{AFV}{RGV}$, which is zero under a no-slip condition and unity under a no-traction condition. Many aspects of slip are discussed by Weiss [123].

The objective of the experiment is to examine the driver's ability to control his vehicle more effectively in a slip-producing situation when he is given direct information about the amount of slip. Ordinarily, slip information is available in the form of auditory cues from the engine and running gear and from seeing a rapid increase in speed indicated on the speedometer which is not consistent with the perceived speed. This slip-meter experiment constitutes a study in which careful control of the information available will allow us to determine;

a) the usefulness of each of the types of indirect information (i. e., visual cues, auditory cues, speedometer), and

b) the additional gain in driver effectiveness, if any, which comes about when a slipmeter is made available to the driver.

The vehicle for this experiment is an automobile equipped with treadless tires and appropriate speed transducers, electronic circuitry, and recorders. The driver will be instructed to accelerate the auto through a short distance on a slippery track, trying to maximize speed and minimize slip. To be recorded are the fifth-wheel velocity, speedometer velocity, slip (as indicated on the slipmeter), the integral of slip, and the time required to traverse the track. Other measures may be derived from the basic data.

The display conditions will vary from trial to trial. At one extreme, the driver will not see the speedometer or slipmeter, and white noise will mask the auditory cues. At the other extreme, the driver will have available all auditory and visual information. The relative importance of the different types of information may be determined by comparing the results of the various display combination conditions.

5. ENVIRONMENT

5.1 Introduction

Interaction between vehicle and environment provides the basis for land locomotion. The term terrasphere has been applied to the medium through which ground vehicles travel, in analogy to the atmosphere as the medium of air transport and the hydrosphere as the medium of water transport. It is the object of environmental analysis to provide an adequate engineering description of the terrasphere for purposes of the vehicle designer, selector and user.

Two general approaches to characterizing the terrasphere are possible: statistical and deterministic. Because of the world-wide complexity of the land locomotion environment, there is a strong tendency to resort to statistical aggregation of mobility-significant terrain descriptors. One must recognize, however, that every environmental descriptor has a value peculiar to every point in space and can be treated as a field. Sampling of the environment on a line, area or volume basis must thus take into account the fact that the sampling process may distort the field by averaging and consequent loss of resolution. All attempts to classify the terrasphere into so-called homogeneous regions must face this problem. To achieve rigor in environmental classification, the environmental scientist must be able to quantify the constraints within which the classification applies.

Detailed environmental surveys are necessarily of restricted geographical scope and studies of broad scope are necessarily of severely

(55 - 60)

limited detail. Our initial effort has been aimed at coarse generalizations applicable on a world-wide basis (Section 5.2) and at the development of high-speed techniques requisite to the efficient processing of detailed environmental data (Section 5.3).

5.2 Prospective of Global Environment

Although there will be considerable feed-back from terrain-vehicle studies as our knowledge in this area grows, there are many well-established impediments to ground mobility -- e.g.:

Soft Soil
Slopes
Streams
Vegetation
Cultural Features(hedgerows, bunds, etc.)

An inventory of our present knowledge of the world distribution of these factors is considered desirable as a first step toward augmentation of the environmental data base for mobility purposes. In this connection, it is not considered sufficient to say that there is a lack of knowledge or that the available knowledge is unreliable. Both coverage and reliability are matters of degree, and we should be in a position to say how insufficient our knowledge is and how bad or how good are our present methods of evaluating the environment.

5.2.1 Soft Soil

Soft soil can occur at least part of the time in most of the militarily significant parts of the world. Conditions conducive to soft ground are flat to gentle slopes and humid climate.

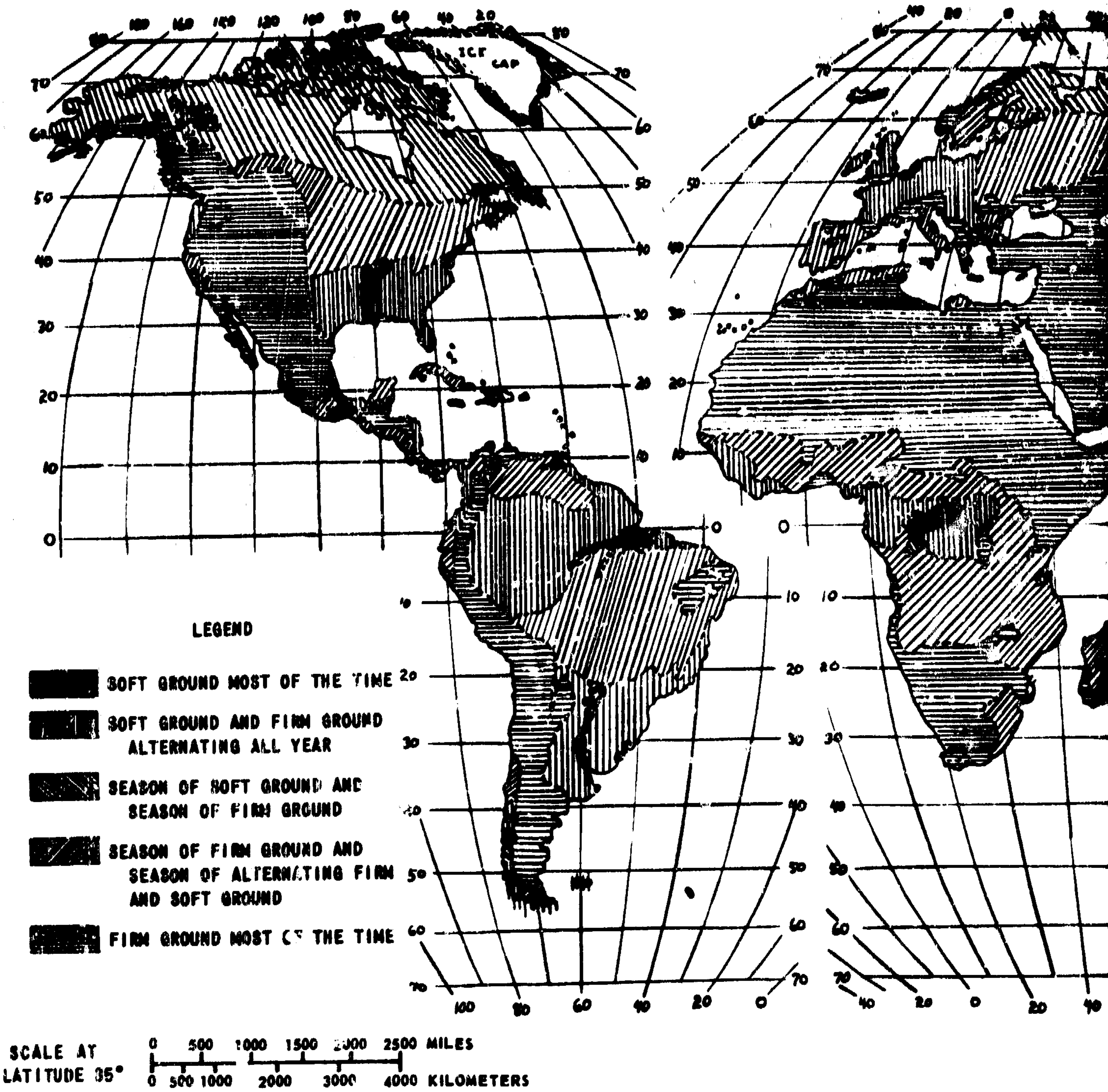
As shown in Figure 5-1, the land areas of the world can be broadly classified into five soil strength regions. The map was produced by combining all, or parts of three classificatory maps.[130] A climatic regions map was used to locate areas of the world with dry seasons, wet seasons, permanently frozen ground, etc.; a soils map was used to locate prominent alluvial areas; and a lithic map was used to locate mountainous regions. Specific soft or hard ground properties were assigned to each climatic, lithic and soils region. The regions of individual properties, when combined, produced the Soil Strength Regions map. For example, an alluvial soil in a region with no dry season would be considered soft most of the time because soft soil problems could be encountered all year round. However, if a high mountain region was located in the same climate type, the region would be considered firm because high mountains are generally bare rock.

Soils are considered soft when they are at or near field moisture capacity and firm when they have 90% or less of this amount. It is recognized that dry sand may also be soft, but such areas are not indicated on the map.

The five divisions of the map are as follows:

1. Soft ground most of the time - This type requires that there be alluvial soil, no permanently frozen ground and no dry season. The areas are small in comparison to the others and are contained within the region described next. Only the largest areas exhibiting these characteristics would be mapped at this large scale.

2. Soft ground and firm ground alternating all year - This type requires that the land be located above river valley level, have no permanently frozen ground and no dry season. It lies astride the equator, going farther poleward on the east sides of continents. It also occurs on western



SOIL STRENGTH REGIONS

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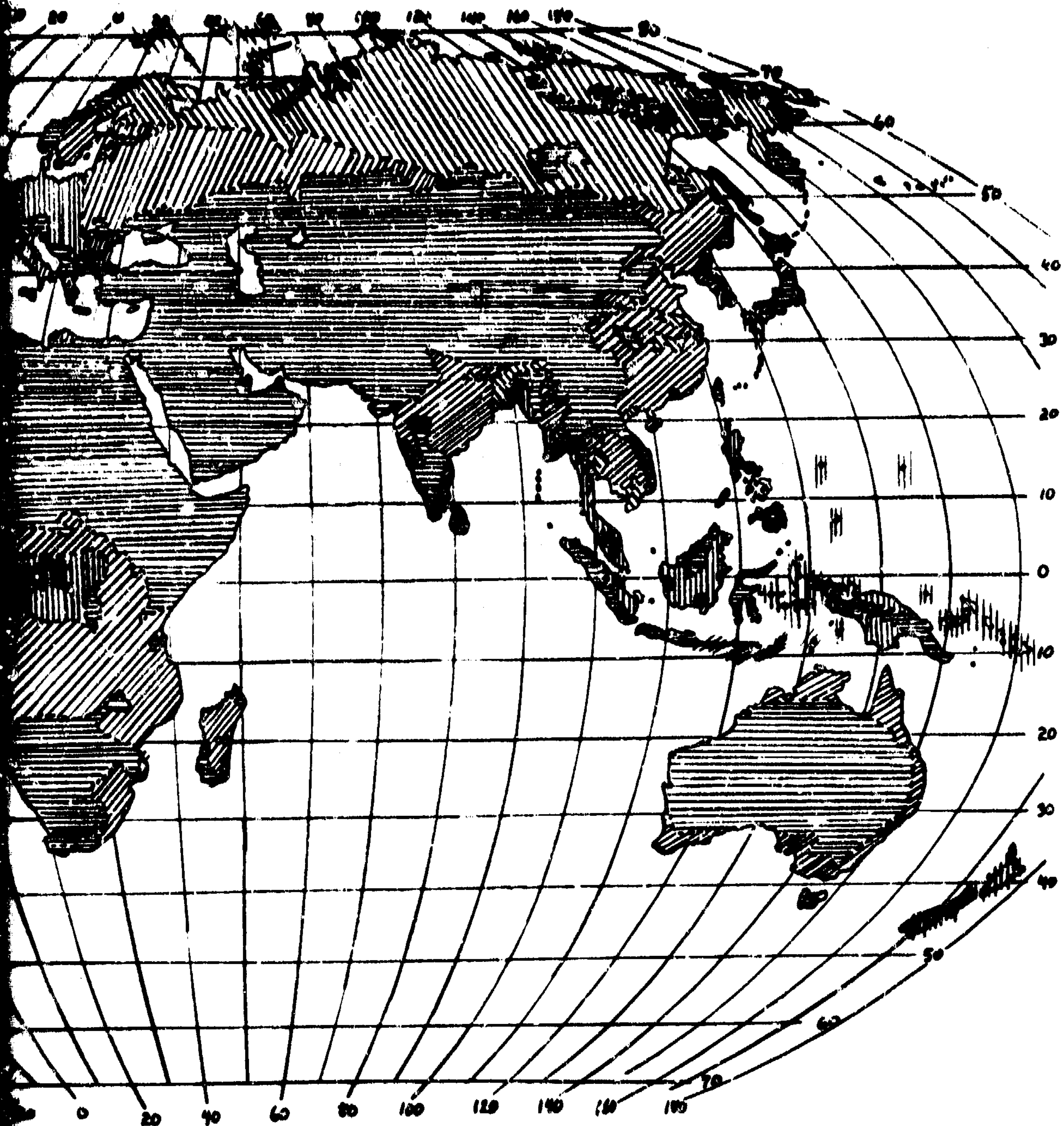
A



B

RENGTH REGIONS

Figure 5-1 WORLD SOIL STRENGTH REGIONS

sides of continents poleward of 40° latitude and as far inland as marine influence can prevent cold winters.

3. <u>Season of soft ground and season of firm ground</u> - The largest areas of this type occur under subartic and tundra conditions. The surface is frozen solid for over half of the year and during the summer swampy conditions prevail. In all except the southern border permanently frozen ground occurs a few feet below the surface. Small tracts of the type also occur in low latitudes on alluvial soil with a pronounced dry season.

4. <u>Season of firm ground and season of alternating firm and soft ground</u> - This type occurs on land which lies outside of river valleys in two different kinds of locations. It can adjoin dry climates and have one dry and one rainy season or it can lie on the eastern and interior parts of continents in middle latitudes and have one season of frozen ground and one warmer season with rainfall exceeding evaporation.

5. <u>Firm ground most of the time</u> - This type has mountains and/or dry climate. In the mountains the soil is generally coarse and shallow or entirely lacking. Rainfall generally runs off rapidly because of steep slopes. In dry climate, soils are coarse and the vegetation cover is sparse. The meager rainfall quickly soaks in or runs off.

The occurrence of soft soil can be mapped in much more detail. For example, seasonal or monthly maps of soft soil conditions can be developed to provide guidance, on an area basis, as to the time extent of soft soil conditions. The severity of these problem conditions, when they occur, is determined by the specific nature of the soils in a given area, particularly their strength response to moisture near field maximum levels.

This point has been addressed in a map published by the Waterways Experiment Station, in which the world distribution of soil strength under wettest conditions is displayed.[131] According to the data comprising this map, WES estimates that very soft soil (RCI < 25) occurs in some 6.5% of the world land surface, soft soil (RCI between 25 and 60) in approximately 17% of the world land surface, and firm soils (RCI > 60) in the remaining 78%. As pointed out by WES, however, these area percentages must be interpreted in terms of their geographic distribution to fully appreciate the threat to mobility posed by soft soil. A world-wide summary of soil type information is presently in progress to supplement climatic inferences and is expected to provide further insight into the severity of soft soil problems in space and time. A major input to this summary is the extensive work of the World Soils Geography Unit at Hyattsville, Maryland.

5.2.2 Streams

Soft soil on upgrades is a significant cause of actual vehicle immobilization. Its most common occurrence in otherwise-negotiable terrains is in stream banks. Where fine-grained unconsolidated material is thick enough to occur in deep gullies, special stream-exit tactics are required. Our study is investigating hydrolic, soil mechanical and geomorphic relations and the statistical distribution of steep, high, soft stream banks in firm, level or rolling terrains.

Statistical assessment of the occurrence of critical features associated with stream banks is necessary for vehicle design and planning. For this purpose, it is convenient to define the sample space in terms of the distance between skyline ridges. Developed for aircraft masking studies, the concept of skyline ridges denotes major watershed divides separated by a valley of depth ΔZ, subsequently referred to as local relief. The

probability, p(SXP), that a stream exit problem will be encountered by a vehicle in driving from one skyline ridge to the other provides a probability measure for the occurrence of problem stream banks. For undissected depositional terrains, p(SXP) is substantially zero, because depositional slopes are generally less than the gradeability of the vehicle. In erosional terrain, however, stream banks can be much steeper than prevailing slopes as computed from local relief. In such terrain, it is not gradeability which limits stream exiting but the ability of the vehicle to surmount vertical obstacles. This capability, expressed as the height of the highest vertical obstacle which the vehicle can negotiate, is referred to as Vehicle Vertical Obstacle Capability (VVOC).

Consider Figure 5-2, which presents a generalized stream bank profile. Note that the slope of the stream bank is steepest on that portion of the bank where the zone of saturated soil is exposed. This region of exposed saturated soil, where bearing strength is minimal, extends to some height h above the steam bed and may be regarded as a vertical obstacle of that height. A stream exit problem exists if h exceeds VVOC, the vehicle vertical obstacle capability.

A method for predicting the occurrence of problem stream banks can be postulated on the premise that p(SXP) increases as local relief ΔZ increases. On sufficiently flat terrain, p(SXP) should approach zero, because ΔZ would be negligibly small and the height of critical stream banks would nowhere exceed ΔZ. At the other extreme, however, p(SXP) might be expected to approach one, because a single valley can exist as a deep, impassable gorge.

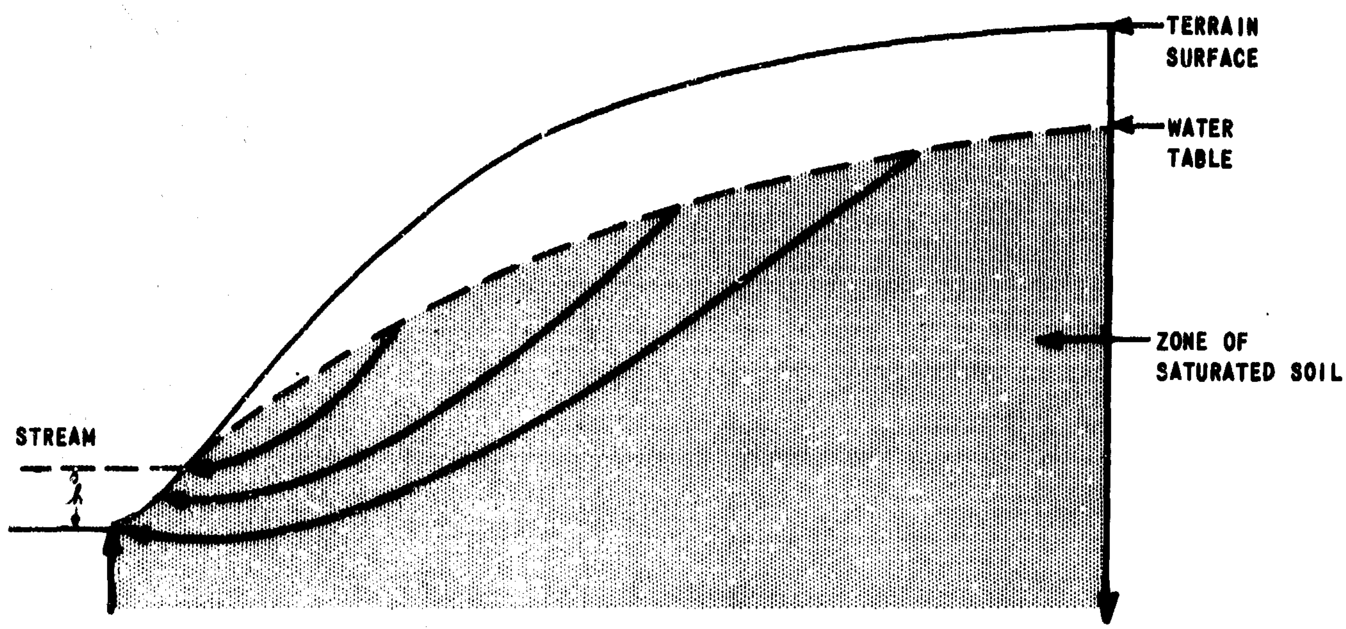


Figure 5-2 IDEAL FLOW PATTERN IN UNIFORM PERMEABLE MATERIAL

The deepest gorges in the world are found in the highest mountains, the Himalayas. The Bjagerathi, a tributary of the Ganga, traverses the range in a slit 600 feet deep. The Indus drains Kashmir through a valley cut 17,000 feet deep.[132] The evidence for valley depths asymptotic to 15,000 to 17,000 feet, slightly over 1/2 the peak elevation of the Himalayas, is rather convincing from an inspection of Army Map Service 1/250,000 map coverage. Several gorges along the Indus, as well as the Kosi and sources of the Ganga, show depths in this range. Using $\Delta Z = 17,000$ feet as a maximum, therefore, one can write as boundary conditions

$$p(SXP) = \begin{cases} 1 \text{ if } & \Delta Z \geq 17,000 \\ 0 \text{ if } & \Delta Z \leq \text{VVOC} \end{cases}$$

and it can be assumed that p(SXP) varies continuously over the range $0 \leq p(SXP) \leq 1$ as ΔZ varies continuously over the range $\text{VVOC} \leq \Delta Z \leq 17,000$. Thus $p(SXP) = f(\Delta Z)$, and an approximation to this function is afforded by

$$p(SXP) \quad \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{\log \Delta Z} e^{-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)^2} dx$$

where m and σ are appropriately chosen constants.

To estimate m and σ, a study was made of air photographs and a No Go criterion applied to observed stream banks.[133, 134, 135] The No Go criterion used was a stream bank steeper than 60% at least 2 feet high. This is the specified performance of the M113 armored personnel carrier, although not quite achieved in the SWAMP FOX II field tests. It is rather typical, however, of the state-of-the-art of conventional military crawler

design. In each soil survey, 10 first-order valleys were sampled in the important catenas corresponding to the major lithologies. Direct routes were laid out across the valleys and the percentage with No Go stream banks estimated. This may correspond to the situation of a common tracked combat vehicle attempting to gain the next ridge without detailed path selection.

Steep 2-foot banks on air photographs can be estimated by parallax or oblique measurement, not available in the soil surveys used, or shadow length. Such estimation is straightforward within the resolution of the photography, which is near the limit in the sample cases, once the solar angle has been determined from date, time, latitude or known objects.

The resulting photo-estimates are the basis for the proposed hypothesis that p(SXP) is related to valley depth ΔZ.

The preliminary data shown in Figure 5-3 suggests that

$$m = \log 100 = 2$$

and

$$\sigma = \log 6 = 0.78$$

Therefore,

$$p(SXP) \approx \frac{1}{0.78\sqrt{2\pi}} \int_{-\infty}^{\log \Delta Z} e^{-\frac{1}{2}\left(\frac{x-2}{0.78}\right)^2} dx$$

On hard ground, VVOC varies from 2 feet for presently deployed rigid wheeled and armored designs (24" for M113 APC, 36" for M24 Tank), to 5 or even some 10 feet for projected advanced articulated configurations. The performance costs of increased VVOC as a function of soil strength are inputs urgently required to define the environmental measurements needed for vehicle-deployment effectiveness studies. In the absence of firm performance data, the bench-mark value of 2 feet was used in the pre-

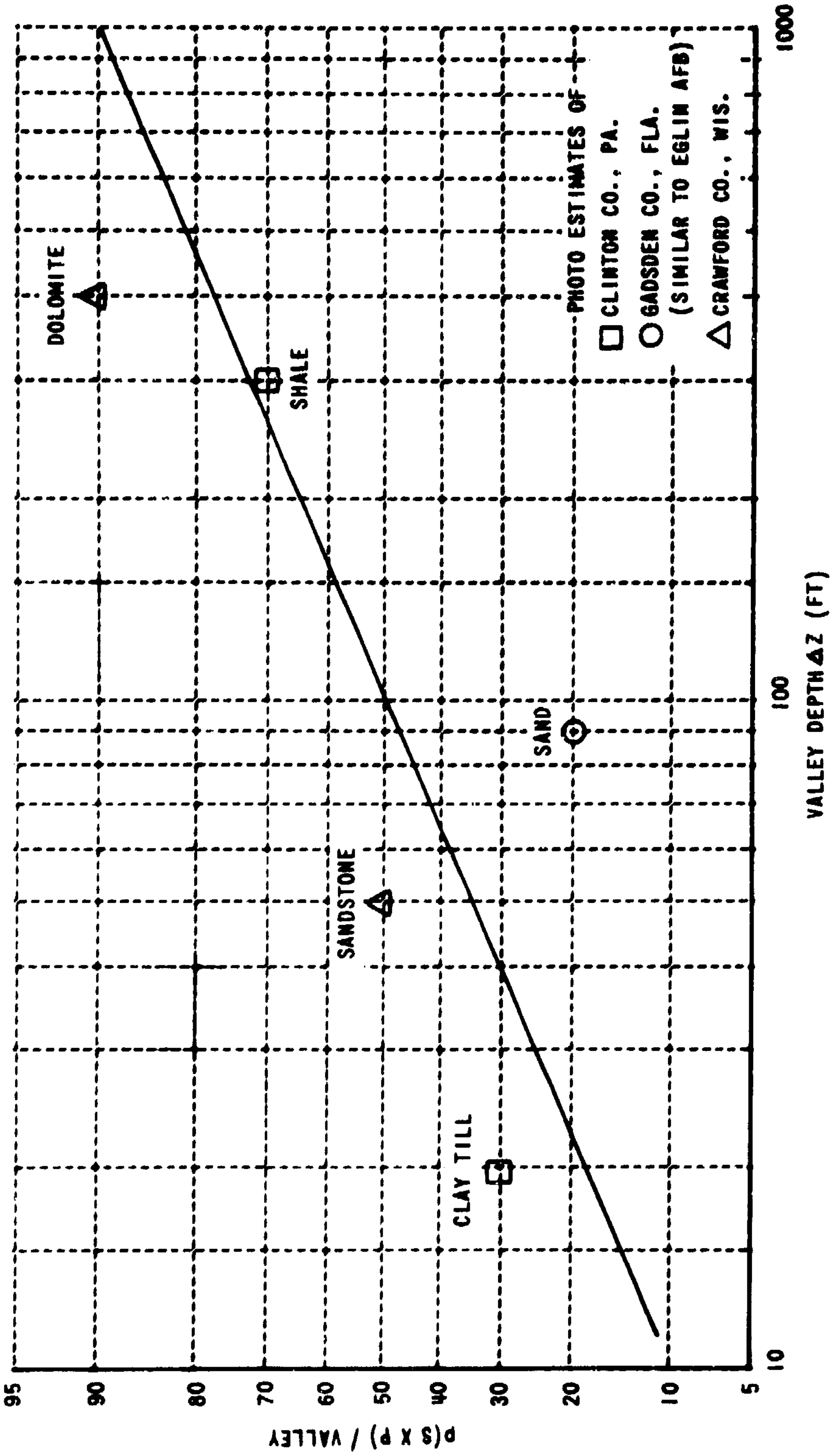


Figure 5-3 PROBABILITY OF STREAM EXIT PROBLEMS AS A FUNCTION OF VALLEY DEPTH

liminary p(SXP) estimates. The proposed equation satisfies the assumed boundary conditions to the following extent:

$$p(SXP) = \begin{cases} 0.998 \text{ for } \Delta Z \quad 17,000 \\ 0.015 \text{ for } \Delta Z = 2 \end{cases}$$

The proposed model is a preliminary attempt to predict the occurrence of stream exiting problems from the limited data available for the world land surface. It is based on the severity of dissection, which is the most obvious physical process controlling the occurrence of problem stream banks. Dissection, as measured by the mappable parameter ΔZ, can then be used to provide a gross regional survey of stream exit difficulties, as shown in Figures 5-4 through 5-9. The uncertainty in ΔZ from the sources available induces considerable uncertainty in the predicted p(SXP); accordingly, only ΔZ is mapped. In a qualitative sense, however, relief values of less than 10 feet represent areas of minimal stream exit difficulty (p(SXP) not exceeding 0.10), 10 feet to 100 feet mild (p(SXP) up to 0.50), and over 100 feet severe (p(SXP) exceeding 0.50).

The base data for the maps (Gerasimov, 1964 [136]) is obtained by estimating the dissection of the Quaternary deposits. These soil parent materials are mappable by erosion process, which can perhaps be related to the amount of uplift and dissection as follows:

Quaternary Deposit	Estimated ΔZ
EROSIONAL	
eluvial (residual)	50-100 feet
eluvial and diluvial	10-200
diluvial	100-500
diluvial and colluvial	200-1000
colluvial	500-2000
colluvial and solifluction	100-1000
bare rock	> 2000

CONTOURS DENOTE MEAN
VALLEY DEPTH IN FEET

Figure 5-4 TERRAIN DISSECTION MAP (ASIA)

Figure 5-5 TEPRAIN DISSECTION MAP (NORTH AMERICA)

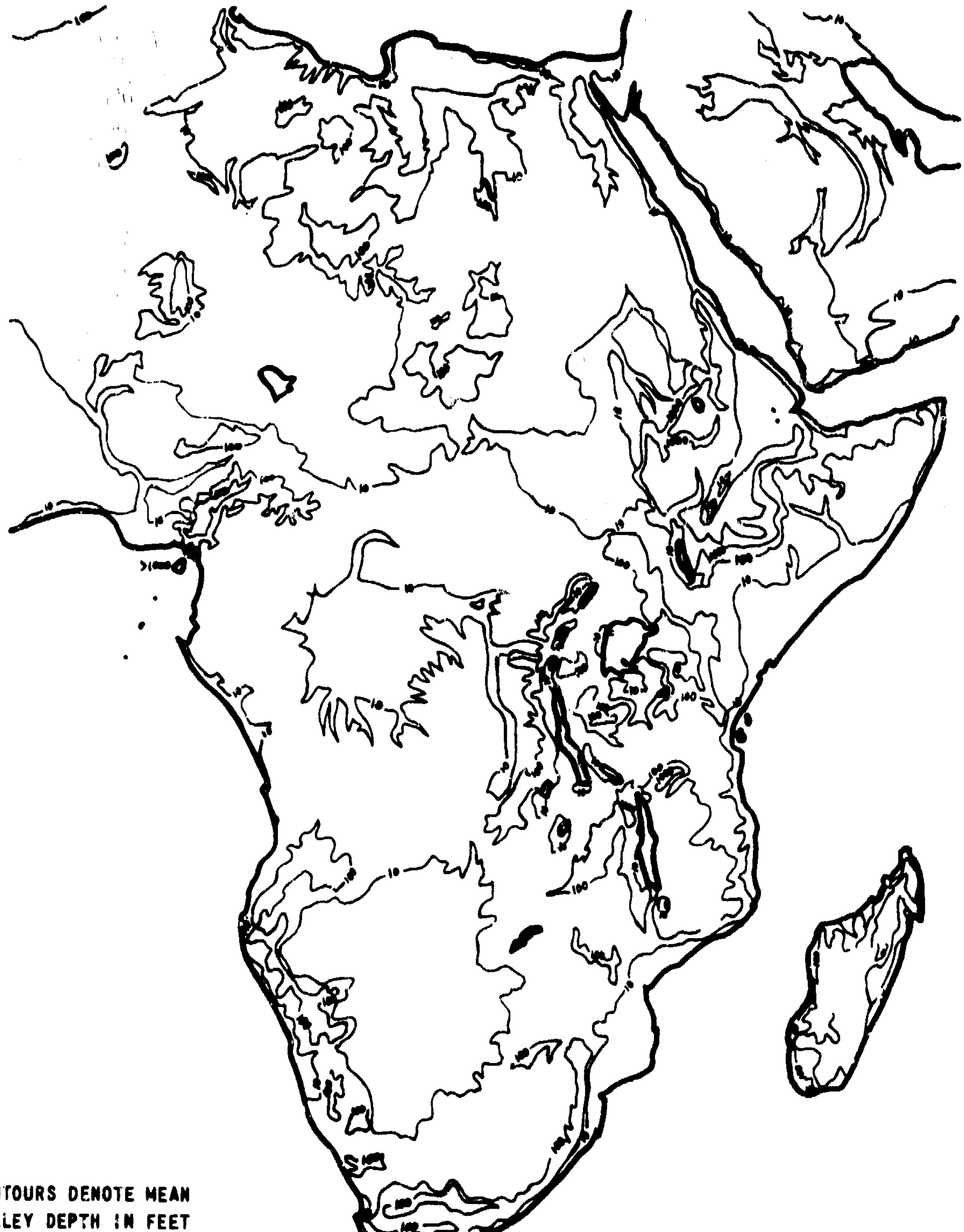
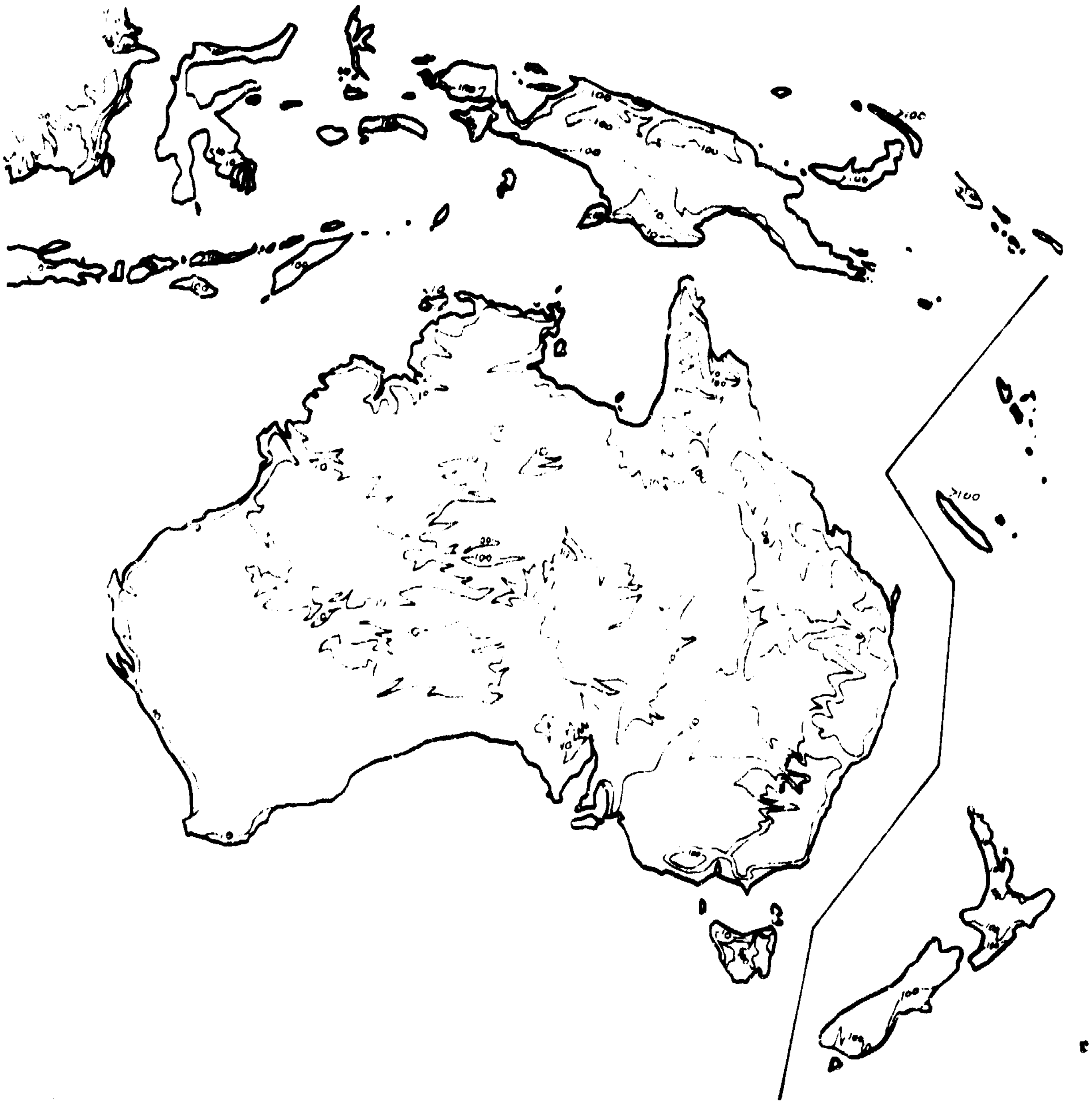


Figure 5-6 TERRAIN DISSECTION MAP (AFRICA)



CONTOURS DENOTE MEAN
VALLEY DEPTH IN FEET

Figure 5-7 TERRAIN DISSECTION MAP (AUSTRAILIA)

CONTOURS DENOTE MEAN
VALLEY DEPTH IN FEET

Figure 5-8 TERRAIN DISSECTION MAP (SOUTH AMERICA)

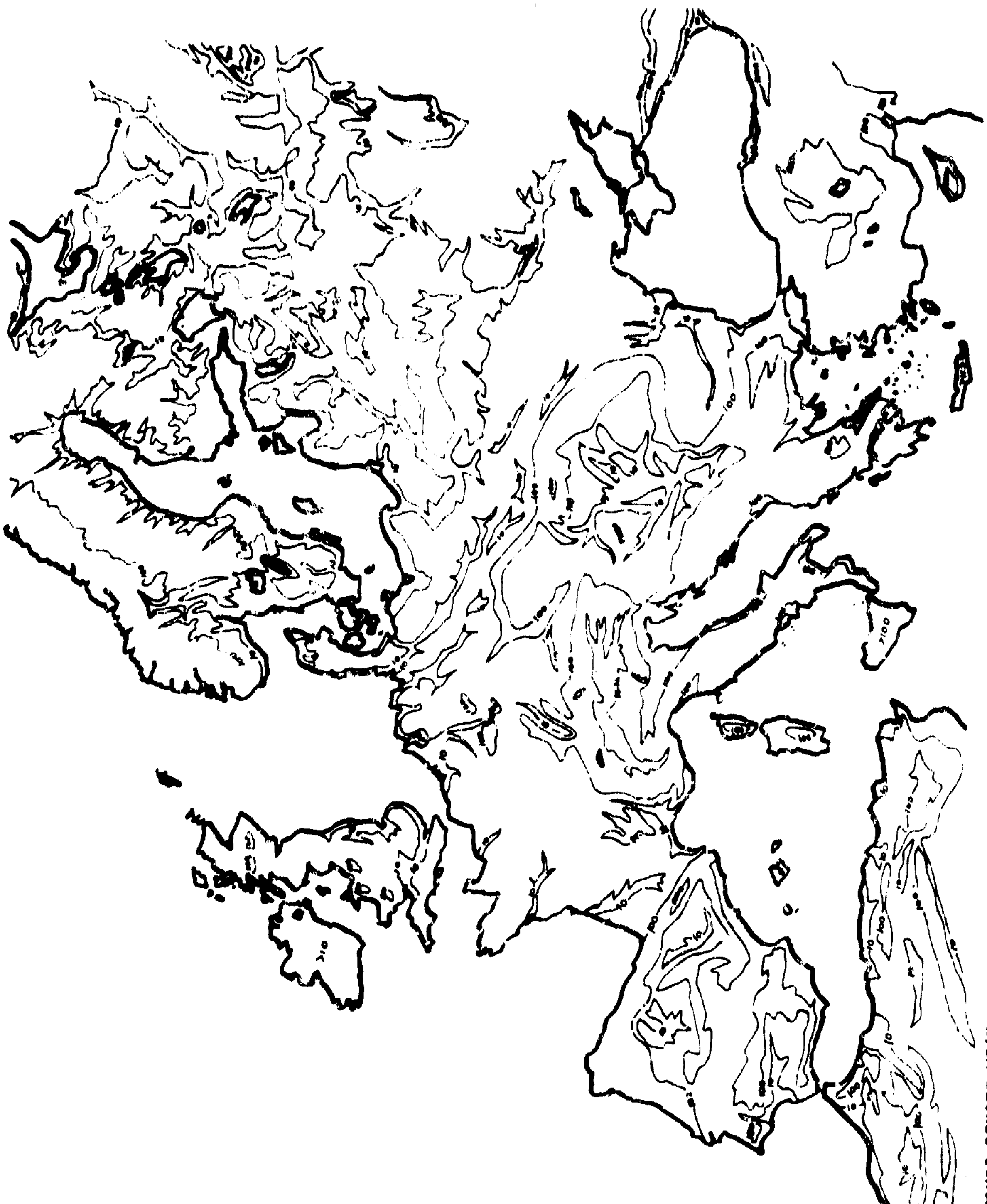


Figure 5-9 TERRAIN DISSECTION MAP (EUROPE)

CONTOURS DENOTE MEAN
VALLEY DEPTH IN FEET

Quaternary Deposit	Estimated ΔZ
DEPOSITIONAL - as subsequently dissected	
marine	0-20
marine and alluvial	0-10
alluvial	50
lake and alluvial	0-10
lake	0-20
lake and proluvial	5
proluvial	2
proluvial + colluvial (pediment)	2-200
glacial moraine	100
glacial outwash	20
aeolian dunes	no streams
aeolian loess	100
volcanics	100-10,000

It is emphasized that the gross generalizations provided by the maps must be tempered by many additional factors applicable locally. For example, as shown in Figure 5-10, valleys of the same depth can have grossly different profiles and these profiles can override the effect of ΔZ per se.

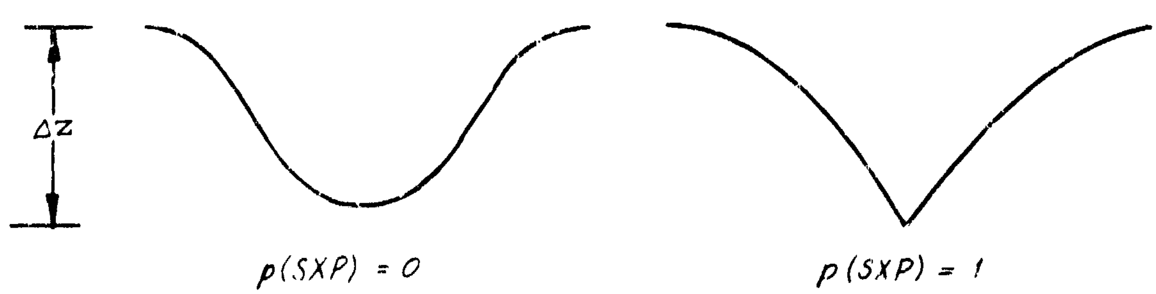


Figure 5-10

Other factors include:

1) **Material particle size in unavoidable high, steep banks.**

2) **Water content of fine-grained materials found.**

3) **Cohesion and composition of clay fraction.**

4) **Geometry of the bank profile with changes of the above, including roots and vegetation debris.**

Work is continuing to incorporate these factors as refinements in predictive relationships, and it is anticipated that increasingly more refined maps of the spatial distribution of stream crossing problems will evolve.

5.2.3 Vegetation

Vegetation can either augment or degrade trafficability, and its effects, as in the case of soils and streams, can be assessed at various levels of generalization. These levels range from world-wide characterization of the great plant associations to the incremental variations in vegetation which affect a particular vehicle traversing a particular path.

Vegetation affects the vehicle/driver complex either through direct physical interaction with the vehicle or through its effect on information sources available to the driver. In the latter instance, vegetation can negatively affect mobility by obscuring the driver's vision or can positively affect mobility by providing visual cues indicating to the driver the nature of the terrain ahead.

An assessment of the general utility of vegetation as a trafficability indicator was undertaken. It was concluded that the state of environmental knowledge of an area provides a criterion for judging the value of plant indicators for mobility purposes. Certainly plant indicator information pertaining to trafficability is redundant in areas in which trafficability is well specified by directly applicable environmental measurements.

Plant indicators will be of most value to persons concerned with off-road mobility, therefore, in areas where environmental conditions are least known. These areas are most common in the very low latitudes and the high latitudes, and particularly in Asia, Africa, and South and Tropical America.

On a world soil map (Figure 5-11)[137] the broad soil groups may be rated as to their potential for plant indicator value as follows.

Tundra Soils -	Important only in special cases but perhaps very important in these.
Podzolic Soils -	Important for special cases of moisture in little known areas.
Chernozemic Soils -	Of least importance of any soil group because environmental conditions are best known here.
Desertic Soils -	Although vegetation is often rather sparse on these soils the plant indicator value may be great because in desert areas the environment is the most inconsistent of that in any broad climatic area.
Latosolic Soils -	These occur in regions least known to people of the mechanized society of the temperate regions and any indicator has potentially great value.
Soils of Mountains -	Here plant indicators will be important only in special cases.

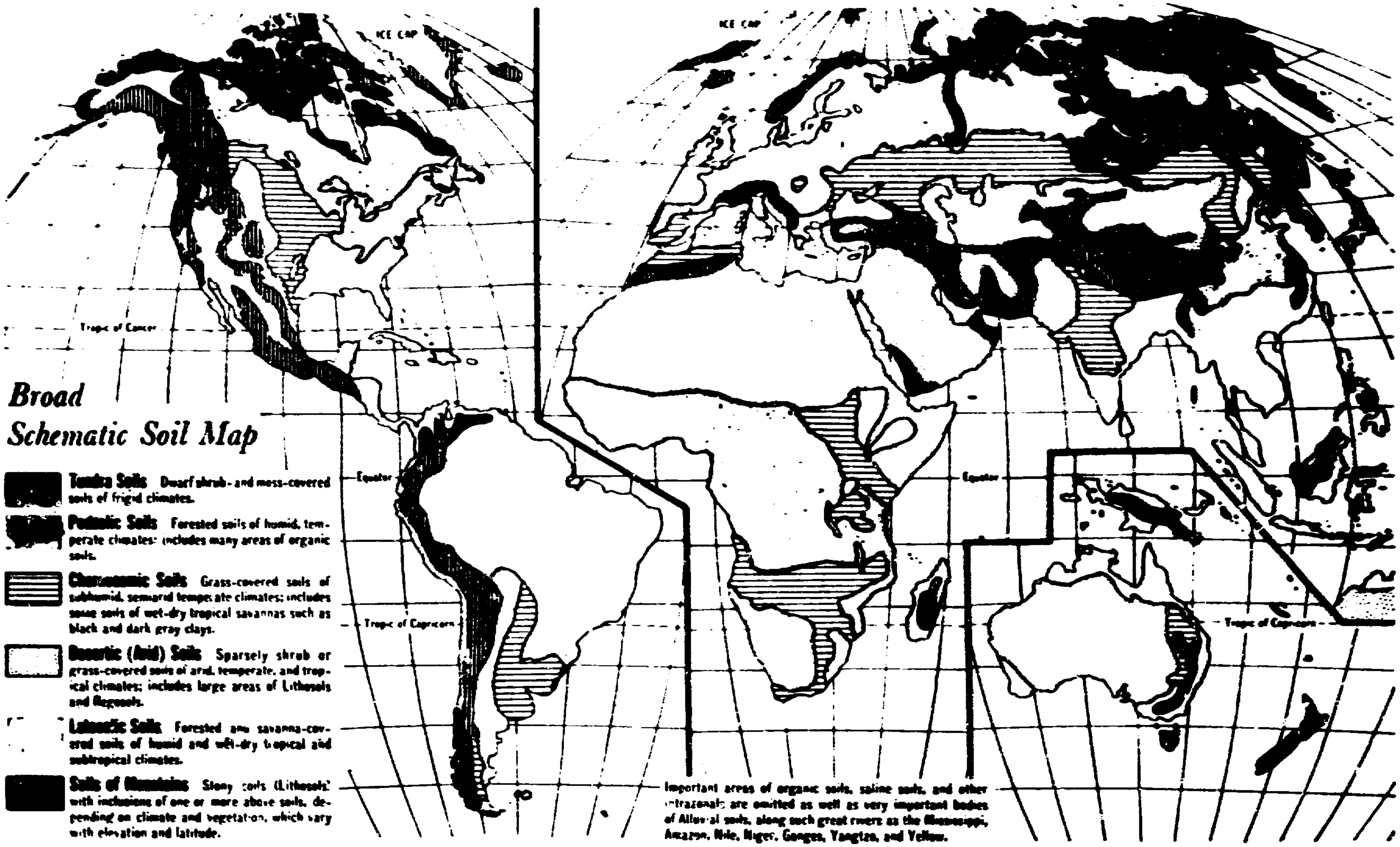


Figure 5-11 DISTRIBUTION OF THE PRINCIPAL SOIL GROUPS OF THE WORLD (Simonson 1957)[137]

Plants can indicate conditions influencing mobility such as soil moisture conditions, soil depth, soil texture, topography, presence of streams, presence of ditches and pits, and cultural land use. During both the El Real[138] and Swamp Fox projects, J. Duke found that several ground conditions could be predicted by using vegetation indicators. It was Duke's conclusion that plant indicators are available on aerial photographs and on the ground. Some of the tropical plants recognizable from the air, which indicate particular ground conditions, were listed by Duke as follows:

1) Espave - Moderately drained soil; half covered roots to 1 ft. high radiating from the trunk.

2) Cuipo - Well drained soil; half covered roots radiating from a swollen trunk.

3) Guaruma - Moderately drained soil with much undergrowth; small prop roots from a soft trunk.

4) Negra jorra - Poorly drained soil adequately firm for light vehicles; visibility practically nil below 2 meters.

5) Mangle negro - Tidally inundated to swamp soil; trafficability and visibility good as far as the vegetation is concerned.

6) Mangle colorado - Tidally inundated swamps; density of stout prop roots makes mobility almost impossible.

7) Alcornoque - Swampy soil with tall meandering buttresses and small loop roots.

8) Cativo - Swampy soil with frequent microtopographical mudholes; visibility good; no buttresses.

Conceivably, therefore, plants might indicate problem regions in the terra-sphere just as cloud formations indicate to an aircraft pilot the prospect of turbulence in his flight path.

The interrelation between vegetation and other features of the environment is certainly not subject to question. It finds expression over a spectrum ranging from the scouting anecdotes of Western frontier days to present life zone concepts, and its value in airphoto interpretation is well established. In general, however, the photointerpreter will continue to stand as transducer between the source of information and its application at the operational level, just as the meteorologist serves as interpreter to translate atmospheric phenomena into flight operation terms. Neither the pilot nor the vehicle driver is enough of a specialist to make extensive use of environmental cues directly, and upgrading their capability in this regard must be purchased at the expense of obvious tradeoffs in their other functions. For the present, therefore, it is considered that the vegetation indicator concept, like other environmental interrelationships, belongs properly in the domain of the environmental scientist and will be implemented most effectively through his continuing efforts to improve the environmental data base for mobility.

5.3 Environmental Analysis and Data Processing

Perhaps the most impressive feature of the environment is that there is so much of it. Its omnipresence is no less imposing than its complexity, however, and the environmental scientist, impaled on the two horns of a dilemma, must continually seek compromises with reality. These compromises generally are effected by aggregating the environment into classes which, for the purposes at hand, are regarded as relatively homogeneous. Variations within a given class are considered negligible under the immediate circumstances, but it is recognized that the scale of these variations may be crucial in a different context.

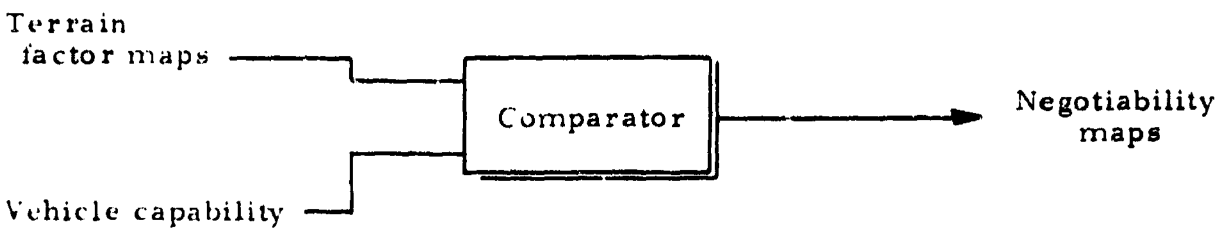
High speed processing of environmental data, made possible by modern computing systems, has both assisted and thwarted environmental analysis. It has made possible the rapid manipulation of environmental data, but at the same time has thrown into harsh perspective the enormity of the associated data acquisition and retrieval problems. Elaborate models employing environmental inputs are of little value unless they are properly scaled to our ability to stuff the gaping maw of the computer with environmental hay. The need to reconcile these conflicting requirements realistically demands the development of a data processing methodology differing substantially from the conventional "brute force" approach of ever larger computer storage capacity and ever shorter access times. Ultimately, computer systems, like their human counterparts, must acknowledge the limitations of finite resources in dealing with a continuum capable of saturating any conceivable storage bank. A major consideration, therefore, is to pose questions in a framework compatible with our ability to supply and manipulate the requisite input data. As a result, one must stand ready to abandon a deterministic model of the mobility process when the sheer mass of data dictates the desirability of a statistical approach. Our methodology studies are directed toward both types of computer processing, but present concern is primarily with data processing involved in a simple deterministic model of the mobility process.

Existing vehicles have come into existence through a process of evolution: a vehicle is designed, tested, redesigned and retested until satisfactory performance is achieved. The process is partly a conscious one and partly a more or less unconscious one in which improvements occur over a relatively long period of time in response to deficiencies which show up as the vehicle is used in the field.

As noted in Section 2.2 an attempt is being made to accelerate this evolutionary process by simulation. An initial vehicle configuration, either an existing hardware item or an intelligent

first-guess "paper" vehicle, is "driven" over a class of terrain as represented by factor maps in typical missions and its ability to accomplish these missions noted. Deficiencies are corrected by parametric variation of vehicle specifications, and iterations are performed until the desired degree of match between vehicle and terrain-mission complex is realized.

The system, very briefly, is as shown in the following sketch.



Comparison can be made on single criteria, such as soft-soil trafficability or slope-climbing ability, or on multiple criteria. Vehicle specifications, in a sense, serve as thresholds for dividing the terrain into disjoint sets: negotiable and non-negotiable. In multiple thresholding, the final negotiability map is the logical intersection of all the negotiable ("Go") sets or, more generally, is the result of thresholding a suitable discriminant function which takes into account the interaction of the several constraints.

Computer mapping techniques are under development for this purpose. Data from existing maps can be expressed to the IBM 360 computer via the Flying Spot Scanner, and thresholding can be performed by spatial filtering routines. In cases in which it is desired to interpolate values of terrain features not presented in the input maps, a routine called CAMERA (Computer Algorithm for Mathematical Extension of Running Areas) developed at CAL under another program[139] is available for this purpose.

5.3.1 Flying Spot Scanner

In the Flying Spot Scanner, a short-persistence cathode ray tube is used to illuminate a transparency in which the desired information is encoded. The present Laboratory equipment employs an electron beam having a half power width of approximately 0.002 inch. The transparency is 3 inches square, and the beam can be positioned at any point in a 1024 x 1024 matrix. Scanning and reading capability is such that any data position in the transparency can be located and read out in approximately 10 microseconds, but it must be realized that the system time constant must be interpreted dynamically. The system is designed to recognize 64 levels of transmission, but noise introduces uncertainty to the extent of 5 to 10 levels. The light transmitted through the transparency is fed to a photo-multiplier, which converts it to an electrical signal. At present, the electron beam scans in a fixed raster, but it could be programmed for random access to data-storage locations.

Maps such as the MERS factor family maps can be photographed to produce a transparency suitable for presenting to the Flying Spot Scanner. Areas on these maps representing different levels of soil strength or obstacle severity are represented by different types of shading or cross-hatching, and these shadings are recognized by the scanner and converted to digital form. Increased discrimination ability can be achieved either by preprocessing the original map (e.g. by opaquing) or by applying spatial filtering techniques such as integration or differentiation to the data as read from the transparency before performing the desired thresholding.

5.3.2 CAMERA Routine

In the CAMERA routine, input data in the form of a relatively coarse grid of observations is transformed into output data in the form of a much finer grid of computed values The interpolation of additional points is achieved by means of a generalized response-surface technique applied to

local areas so as to build up the entire global area as a series of overlapped "patches". The method is similar to the approximation of a plane curve by straight line segments, but the form of the patches is not restricted to planes but can take any form considered appropriate to the nature of the surface being represented. In fact, several different species of patches are used, and each local region is represented as a linear combination

$$z = \sum_{i=1}^{N} \beta_i f_i(x, y)$$

where the f_i are (basis) functions of the position coordinates (x, y), z is the output variable, and the β_i are numerical coefficients determined for the local region. The β_i are determined by least squares theory, which degenerates into an exact fit of the input data if N is taken equal to the total number of input points in the local input data array.

After the β_i have been determined, the resulting function is used to compute z for a large number of (x, y) positions. These values can be printed out for explicit observation or can be displayed in map form.

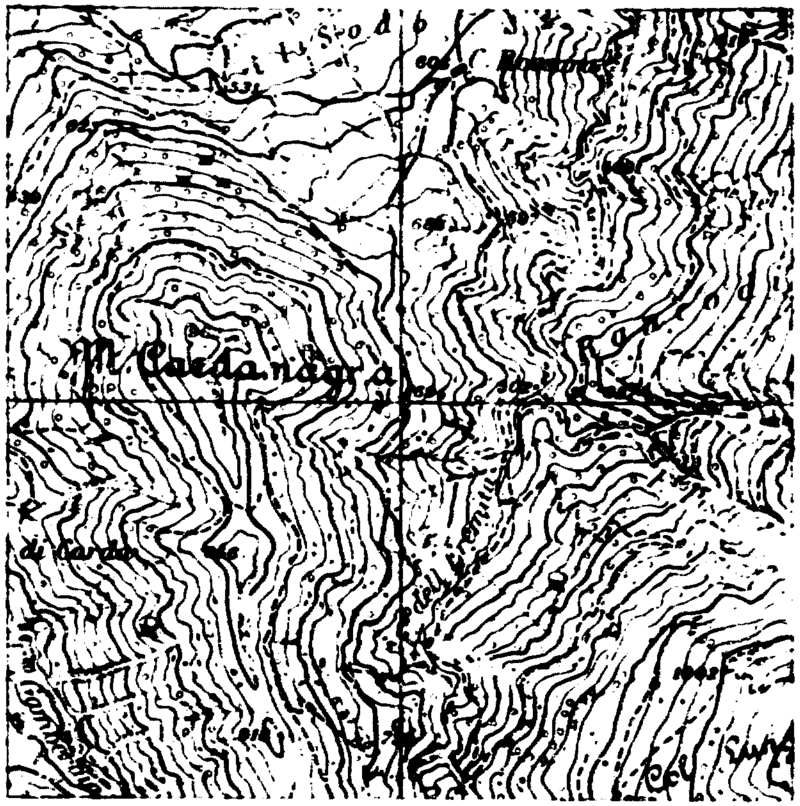
Maps are produced by the CAMERA routine as follows. First, a correspondence is set up between (x, y)-coordinate positions and the positions to be occupied by alphanumeric characters in the output format. Then, each of the interpolated z values is compared with a threshold. If the threshold is exceeded, a chosen alphanumeric symbol, other than a blank, is printed in the format position corresponding to the associated (x, y)-coordinate position. If the threshold is not exceeded, a blank is recorded. The boundary between the blank and occupied regions of the output format constitute a contour line for the particular value at which the output data were thresholded. The procedure can be repeated for any number of threshold levels to produce a separate map for each contour level. Because the distance between lines on the printer is greater than the distance between characters in a line, the maps are elongated in the

vertical direction, but this fact does not interfere with their interpretation and can be removed, if desired, by appropriate scaling.

An example of the CAMERA method is presented in the accompanying maps, Figures 5-12 and 5-13. Input data were taken from a topographic map of Italian terrain, reproduced in both figures for comparison purposes. A total of 289 elevations, read from the original map on a regular 17 x 17 array, was transformed into more than 16,000 interpolated elevations. In Figure 5-12, these interpolated elevations are thresholded to produce elevation contours at 525, 575 and 775 meters, and are presented to show by comparison with the input topographic map, the extent to which the original contours are recovered in the computed contours.

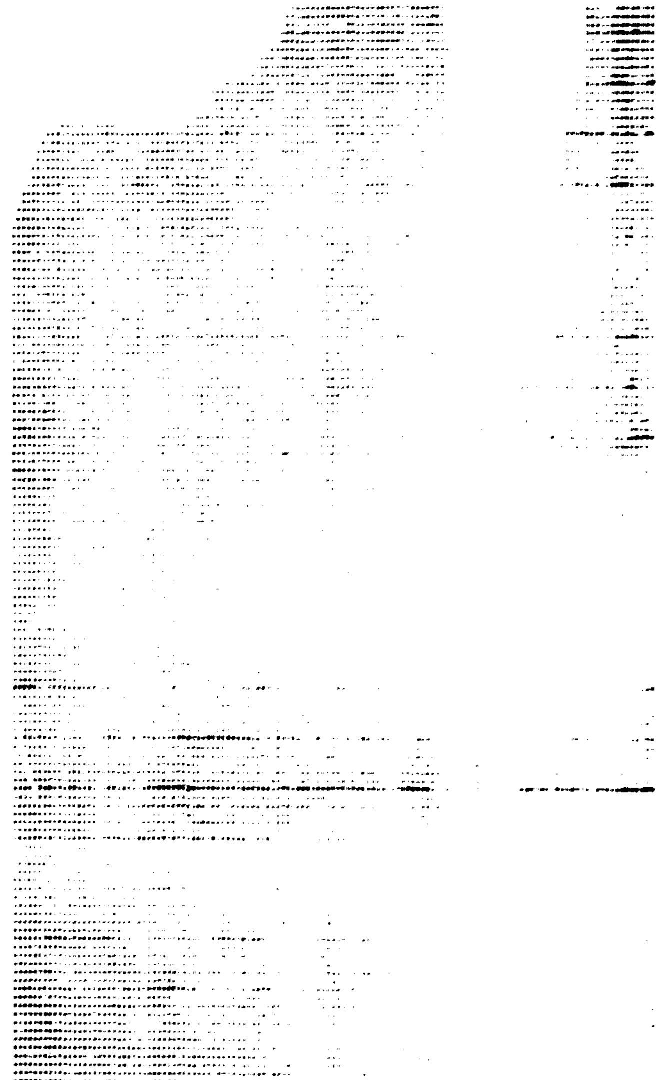
By virtue of the explicit form of the interpolated elevation z, each of the basis functions f_i can be differentiated with respect to position coordinates and the derived functions used to compute a slope "surface". Thresholding of this derived surface then provides slope contours. Figure 5-13 presents three such contours, at 10, 20, and 30 degrees, in comparison with the original input topographic map. The areas contained within these contours may be used to obtain an estimate of the relative frequency of occurrence of slopes of various magnitudes as measured by the corresponding areas affected. The validity of the computed slope contours can be judged by comparison with the distances between contour lines in corresponding regions of the original reference topographic map.

The CAMERA model is considered as a possible means for compressing the essential information content of a set of environmental observations into compact form readily addressable for computational purposes. Caution must, of course, be exercised in its use in order to avoid the pitfalls incident to excessive smoothing. For example, in the case cited above, one is tempted to interpret the slope contours as boundaries between areas accessible and inaccessible to a vehicle with gradeability equal to the contour value. It must be remembered, however,

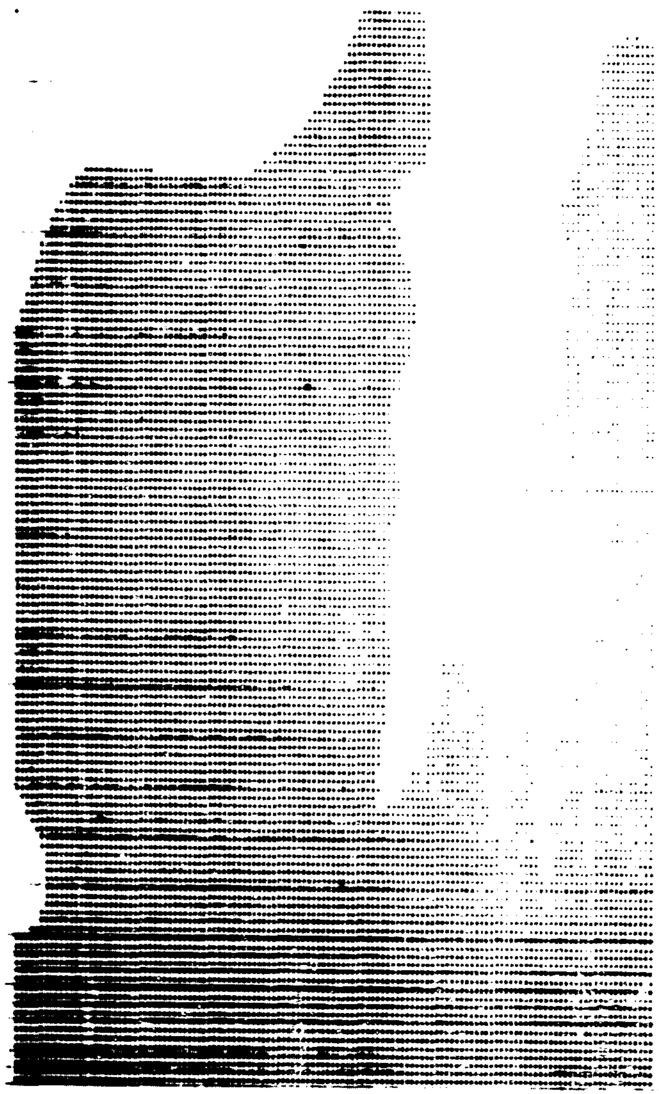


MAP SCALE	1:25,000
SHEET NO.	116 IV SW ARMY MAP SERVICE
SHEET NAME:	PIANELLO, ITALY
UMT COORDINATES:	SOUTHWEST CORNER - 96 E. - 23 N.
	NORTHEAST CORNER - 98 E. - 28 N.

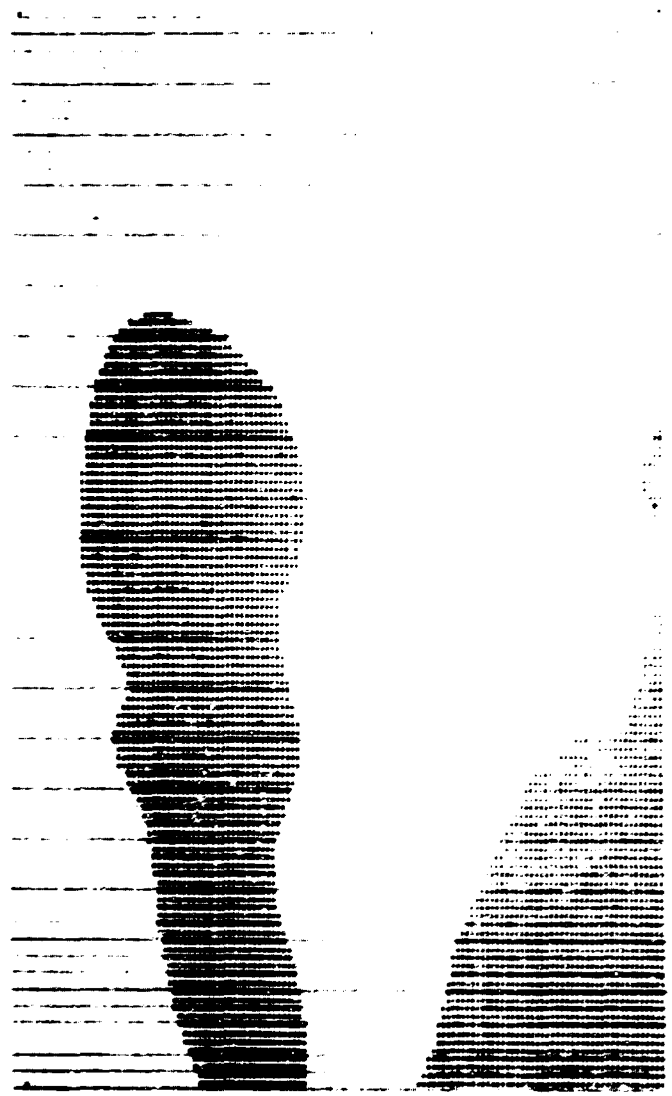
(a) ORIGINAL MAP



(b) CAMERA CONTOUR: PRINTED SYMBOLS REFER TO ELEVATIONS ABOVE 525 METERS

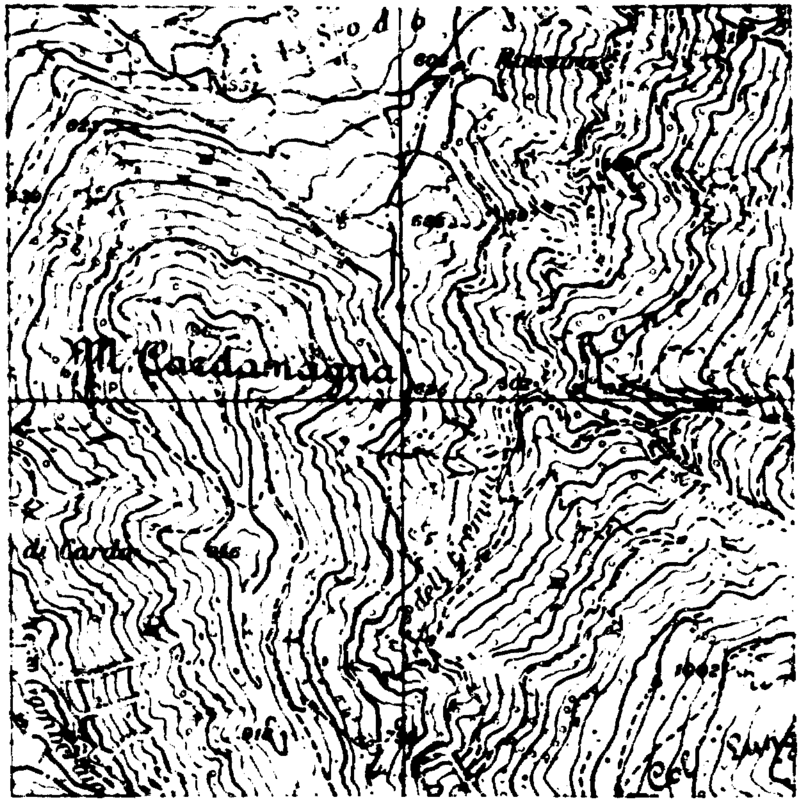


(c) CAMERA CONTOUR: PRINTED SYMBOLS
REFER TO ELEVATIONS ABOVE 575 METERS



(d) CAMERA CONTOUR: PRINTED SYMBOLS
REFER TO ELEVATIONS ABOVE 775 METERS

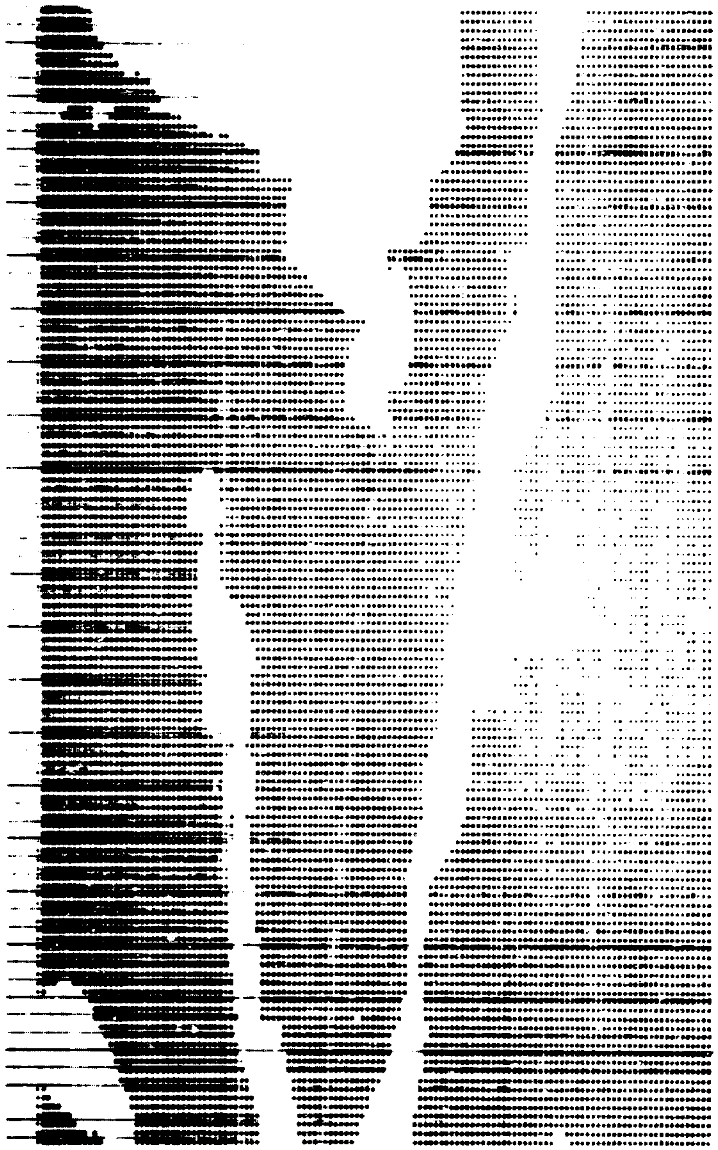
Figure 5-12 ORIGINAL MAP AND CAMERA PRINTED ELEVATION CONTOURS



MAP SCALE	1:25,000
SHEET NO.	116 IV SW
SHEET NAME:	PIANELLO, ITALY
UMT COORDINATES:	SOUTHWEST CORNER - 96 E. - 26 N.
	NORTHEAST CORNER - 98 E. - 28 N.

(a) ORIGINAL MAP

(b) CAMERA CONTOUR: PRINTED SYMBOLS REFER TO SLOPES ABOVE 10 DEGREES



(c) CAMERA CONTOUR: PRINTED SYMBOLS REFER TO SLOPES ABOVE 20 DEGREES

(d) CAMERA CONTOUR: PRINTED SYMBOLS REFER TO SLOPES ABOVE 30 DEGREES

Figure 5-13 ORIGINAL MAP AND CAMERA PRINTED SLOPE CONTOURS

that the slopes, as contoured, are based on an average taken over a distance comparable to the distance between elevation contour lines on the original map used as input and do not necessarily represent slopes locally applicable over distances compatible with the scale of the vehicle.

The need for a field concept of environmental descriptors is therefore clear. Until a mathematical framework is provided for acknowledging explicitly that quantities such as slope and soil strength parameters vary pointwise with position, full advantage cannot be taken of the stock of mathematical and statistical tools available to the present-day environmental analyst. Formulation of such a field concept, and definition of its relation to appropriate probability measures for statistical aggregation of environmental information, will receive attention in the continuation of our program.

6. SOIL MECHANICS

A problem that has held back the development of soil mechanics in comparison to, say, mechanical metallurgy is that of obtaining suitable uniaxial stress-strain relations upon which to base stress-strain relations in more complex loading. The facts that soil has no tensile strength, that its pore water pressure changes under loading and hence during testing, and that it may change volume under load, may be mentioned as examples of added difficulties. Our review[2] of the current status of soil mechanics did, however, reveal that progress has been made toward obtaining rigorous stress-strain data. This has been achieved at moderate strains and low strain rates by measuring pore water pressure during test and by analytical treatment of pore pressure and deformation data obtained in triaxial cylinder tests. In contrast to the common triaxial cylinder testing, such work was held to be a suitable basis for formulation of general stress-strain relations and for their eventual extension to the large strains and high strain rates that are typical of vehicle passage.

Our review of soil mechanics theory and practice lead to three conclusions: (1) The existing techniques of the continuum mechanics of inelastic solid media appear applicable to the formulation of stress-strain relations in soils and to their solution by approximate methods. (2) The formulation of the necessary constitutive equations requires determination of the essential particle and phase properties of the various soil types. (3) Experimental and measurement techniques appropriate for the specific problems to be investigated must be developed.

The research discussed in paragraph 6.1 to 6.3 reflects our choice of the visioplasticity method as a promising approach to studying the mechanics of soil under load. While we currently favor such an approach, we are at the same time continuing to study alternate methods. In

Section 6.4 we summarize a brief study performed by Dr. S. C. Cowin of Tulane University suggesting an approach treating soil as a non-reacting ternary mixture.

6.1 Continuum Mechanics

The specific problem areas related to the formulation of continuum mechanics field equations consistent with soil-vehicle mechanics problems have been outlined in Appendix B, Section 3 of Reference 2. These problems must be mathematically categorized as mixed boundary value problems since both stress tractions and displacements are prescribed on the soil half-space surface. The mathematical representation must also consider material continuity, equations of motion (or equilibrium), geometric or kinematic compatibility and constitutive equations (stress-strain time relations) within the soil mass.

The formulation of even a relatively simple soil-vehicle problem is not mathematically tractable in terms of a closed form solution and attempts to produce a solution must necessarily explore approximate methods. There are further complications since presently an adequate mathematical model representation of the material response characteristics (constitutive equations) of soils is unavailable.

It appears that additional progress in the soil-vehicle-interaction process will be restrained until there is available a better understanding of the soil loading mechanism. This essentially means that a complete solution, in the sense that it satisfies the principles listed above, must be obtained for a prescribed class of problems. For example, attempts to use scaling have generally been of limited value in soil-vehicle mechanics problems. Geometric similarity may be maintained between model and prototype, and expressed in terms of similarity on the deforming region of the soil half space. To maintain dynamic similarity, control must be exercised over a timelike parameter, leading to relation-

ships between length and timelike parameters. However, it can be shown that if, in the constitutive equations, stress depends only on strain, then the similarity condition will be different than if stress depends only on strain rate[140]. In a general problem, where strain and strain rate terms are required, exact conditions of similitude cannot be maintained. Yet, a known solution to a problem would provide guidance in terms of the conditions which lead to a better approximation.

The following discussion, drawing on techniques of the visioplasticity method developed and used to analyze metal forming operations[140, 141, 142, 143, 144] indicates a procedure which could eventually lead to possible solutions in this problem area. The immediate need is to develop the machinery necessary to apply the visioplasticity method to selected soil-vehicle problems. As is indicated, once the required techniques are available, it should be possible to extend these results from model to prototype in a more precise manner using scaling principles, limit analysis theorems and numerical techniques.

Since the stress-strain behavior of soils is crucial in the analysis, considerable effort will have to be expended in this area. A separate section of this discussion is devoted to a consideration of the types of analysis and equipment which are necessary to better define the continuum aspects of the stress-strain-time behavior.

6.1.1 Method of Solution

It is necessary to obtain a solution which may be taken as exact for a given class of problems, and since even a solution to the most elementary problem is beyond a purely analytical description, analytical-empirical techniques must be considered. Many of the features of the visioplasticity method may be applied to soil mechanics and the Cambridge soil mechanics group (Roscoe, et al), using some aspects of the technique, have recently reported some success[145, 146]. The following is a brief summary of basic requirements for such application.

With the visioplasticity method, the velocity field must be experimentally measured; thus, all kinematical terms are assumed to be known in the field equations and the load terms (stresses) are then analytically determined. Figure 6-1 shows graphically the requirements for application of this method to the soil-vehicle interaction process. The experimental measurements are indicated by the E-blocks and these data may be analyzed within different degrees of approximation as indicated by the A-blocks.

E1: Measurements in the Soil Medium

There are two primary tasks connected with these measurements: (a) an evaluation of present methods and the specification of adequate measurement techniques and (b) the determination of suitable generalized inelastic deformation criterion.

E1(a): Measurement Techniques

It has been demonstrated that the relative soil velocity field may be measured with the X-ray technique[147]; however, this technique is expensive and the flow field which may be visualized is limited, tending to severely restrict the model dimensions. The velocity measurement technique should be able to visualize the entire flow field at a given instant and sequentially for small time increments. This latter requirement is absolutely necessary when considering a nonsteady state problem such as the action of a grouser near the soil surface. Some researchers in the field are making measurements where lubricated glass surfaces are used to represent a plane of symmetry through which deformation grids of soil under load may be observed and measured.

Particularly with partially saturated soils, the density must be measured throughout the medium. These variations in density are required in the equations of motion (inertia forces) and the

continuity equation. With the more saturated soils. an attempt should be made to measure the pore water pressures.

E1(b): Determination of Inelastic Distortion Criterion

The relative velocity, measured along the particle path, is used to determine measures of equivalent strain rate and/or equivalent strain. Depending on the manner by which energy is dissipated in the soil, these measures of distortion must be coupled with measures of stress intensity. More precise information on the general constitutive theory for soils should aid in the selection of proper generalized distortion measures. In addition, these generalized quantities must be used to determine the region of positive power dissipation.

E2: Material Response Characteristics

From the standpoint of the vehicle-soil interaction process, it appears the more important material response characteristics are related to the energy dissipation mechanism. Under quasi-static conditions, some soils (sands and normally consolidated clays) have been shown to exhibit properties similar to work-hardening metals but soil tends to flow under conditions where volume changes and the yield condition depend on the mean normal stress.

Soil response is known to be rate dependent, i. e., the yield strength tends to increase with high loading rates. These dynamic properties are important in the soil-vehicle mechanics problem but, because the basic problem is so complex, the initial effort should be directed towards solving quasi-static problems, and then extending the analysis to visco-plastic behavior.

E2(a): Stress-Strain Relations

With triaxial test measurements, Holubec[148] has shown for sands that if the ratio of the stress difference to mean effective normal stress is taken as a function of the deviator strain, then the resulting curve is similar to the work-hardening stress-strain curves for metals. Similar results (Roscoe, et al) have been reported for normally consolidated clays[149, 150]. Most soils, particularly clays, are naturally in a state of over-consolidation. The same technique as used for sands and normally consolidated clays may be useful in establishing stress-strain relations for overconsolidated clays but, in this latter case, a series of curves may be necessary.

Present experimental equipment is somewhat limited in regard to determining stress-strain behavior in general stress space and effort must be directed towards the development of suitable equipment for measuring a specific loading response.

E2(b): Pressure Density Relation

It must be recognized that irreversible volume changes can occur during soil flow and this is one of the primary areas where the description of soil flow will depart considerably from that employed with metals.

D1: Data Correlation

The problem in the data treatment is to establish means by which the results of the velocity field measurements and the stress-strain data can be coupled in a meaningful way. This requires consideration of (a) velocity field data smoothing and

interpolation, (b) establishment of a fixed grid with respect to a moving reference frame, (c) calculation of strain rate, strain and density parameters at each grid point (requires interpolation) and (d) determination of equivalent stress and mean normal stress at each grid point. The region of positive power dissipation (plastic region) must also be determined from the deformation measures.

6.1.2 Analytical Effort

After D1 is completed, there still remains the analytical task of determining the load variables in the region of plastic flow. In general, this may be done in three ways, each requiring a greater degree of difficulty.

With a plane strain analysis, three equations are necessary to solve for the three unknown stresses, i.e., two equations of motion (or equilibrium) and a yield equation. As is indicated in Figure 6-1, A1 is an approximate calculation of the total energy dissipation using the equivalent stress and equivalent strain rate parameters, A2 is analogous to a total strain-type plasticity theory and A3 analogous to an incremental-type plasticity theory. Each analysis becomes progressively more difficult. However, all should be explored in attempting to compare calculated and measured variables.

6.1.3 Extension From Model to Prototype

Since no general analytical method is available to determine the velocity field and since the visioplasticity method relies heavily on experimental investigations, dynamic similarity will be required in any attempt to predict behavior in a given operation. There has been some work in dynamic similitude in plastic deformation. An analogous study is needed for soil behavior but, with soils, additional parameters such as water content and water flow must be included in the similitude studies.

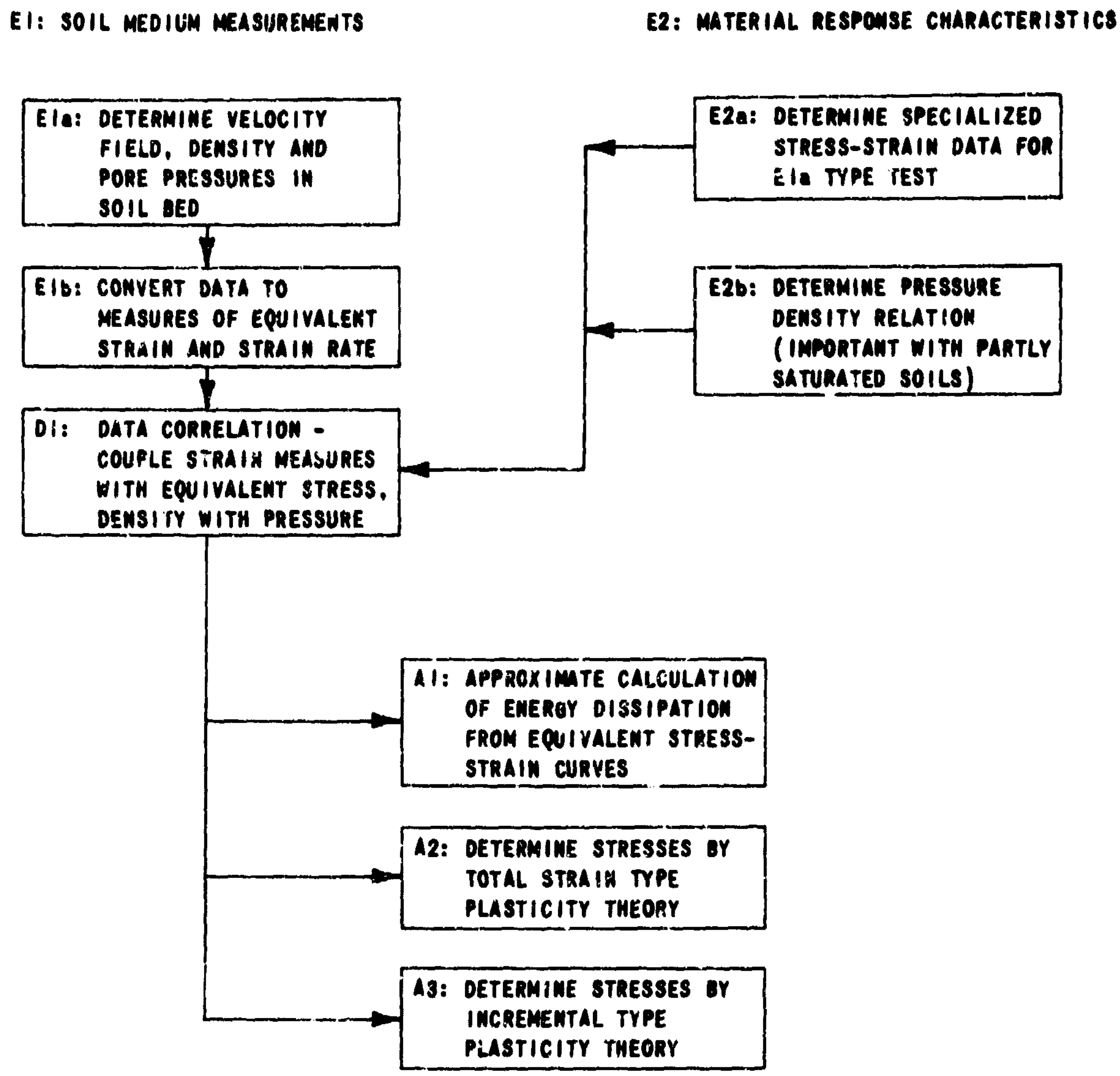


Figure 6-1 VISIOPLASTICITY METHOD IN SOIL MECHANICS

Shabaik and Kobayashi[140] (page 39) list fourteen conditions necessary for similarity between model and prototype in a metal processing problem. It is doubtful that all of these conditions could ever be satisfied. Depending on the more salient features, certain conditions could be maintained but the prototype solution cannot represent an exact solution and only "approximate similarity" should be expected.

For example, in a given situation, geometric similarity can be maintained between model and prototype, while different soils (different constitutive equations) are used in model and prototype. It is unlikely that the similarity requirements relating to the material mechanical properties would be maintained. By proper choice of time and length parameters, it might be possible to satisfy the similarity requirements related specifically to the boundary conditions, continuity and equilibrium conditions. Within this approximation, a velocity field and a stress field could be determined for the prototype. These velocity and stress "solutions" cannot be exact but they might be shown to be appropriate admissible solutions as outlined in the limit analysis theorems of Drucker, Greenberg and Prager[151]. In this manner, these admissible solutions could permit the establishment of upper and lower bounds in the prototype loadings.

Another possible approach where the scaling techniques might be used to determine an exact solution to the prototype problem is to use the approximate scaled solution as the estimated solution vector in a numerical solution to the field equations. The field equations may be represented as a system of partial differential equations or with plane strain as a single equation. Shabaik and Kobayashi[140] show that for a plane strain, Levy-Mises plasticity problem, a stream function ϕ may be introduced to satisfy the continuity equation. In terms of ϕ, the equilibrium equations may be reduced to

$$\frac{\partial^2}{\partial x \partial y}\left(\frac{2}{\dot{\lambda}}\ \frac{\partial^2 \phi}{\partial x \partial y}\right) + \frac{\partial^2}{\partial y^2}\left[\frac{1}{2\dot{\lambda}}\ \left(\frac{\partial^2 \phi}{\partial y^2} - \frac{\partial^2 \phi}{\partial x^2}\right)\right] - \frac{\partial^2}{\partial x^2}\left[\frac{1}{2\dot{\lambda}}\left(\frac{\partial^2 \phi}{\partial y^2} - \frac{\partial^2 \phi}{\partial x^2}\right)\right] = 0$$

where $\dot{\lambda}$ is a prescribed function of the different second partial derivatives of ϕ.

The above fourth-order partial differential equation in ϕ is nonlinear, and even an approximate numerical solution would appear impossible with present methods. The usual numerical technique is to employ an algorithm in which an iterative process operates successively on an initial (or assumed) solution $\overset{o}{\phi}_{i,j}$ the subscripts i and j indicating the discrete approximation at the grid points (i, j). There exists evidence to indicate that, with nonlinear problems, if the initial solution $\overset{o}{\phi}_{i,j}$ is "close" to the actual solution, then the system will tend to converge. Thus, it is suggested that the use of a scaled solution may be a realistic approach to establishing a reasonable initial solution for an iterative scheme.

6.1.4 Stress-Strain Behavior

A given stress-strain test can supply only very limited information concerning the general material behavior and it is necessary to compare the results of different tests. These comparisons are governed by assumptions concerning the general behavior of the material.

The load paths (stress paths) for different tests must be represented in a general stress space. In terms of principal stress (roots of the stress tensor characteristic equation) only a three-dimensional space is required and all stress paths should be represented in this space. Figure 6-2 shows the principal stress space where $\overline{OA}$ makes equal angles with the stress axes, $\sigma_1, \sigma_2, \sigma_3$ and also is normal to the octahedral plane BCD. If the stress path is given by the stress components in the X, Y, Z stress space as defined by the unit vectors

$$\hat{I} = \frac{1}{\sqrt{2}}(\hat{i} - \hat{k})$$

$$\hat{J} = \frac{1}{\sqrt{6}}(-\hat{i} + 2\hat{j} - \hat{k})$$

$$\hat{K} = \frac{1}{\sqrt{3}}(\hat{i} + \hat{j} + \hat{k})$$

then it is readily shown that the stress component in the Z direction is proportional to the first invariant of the stress tensor while the shear component in the octahedral plane is proportional to the second invariant of the stress deviator tensor. The pore pressure, or difference between total and effective stress influences only the Z component in this stress space.

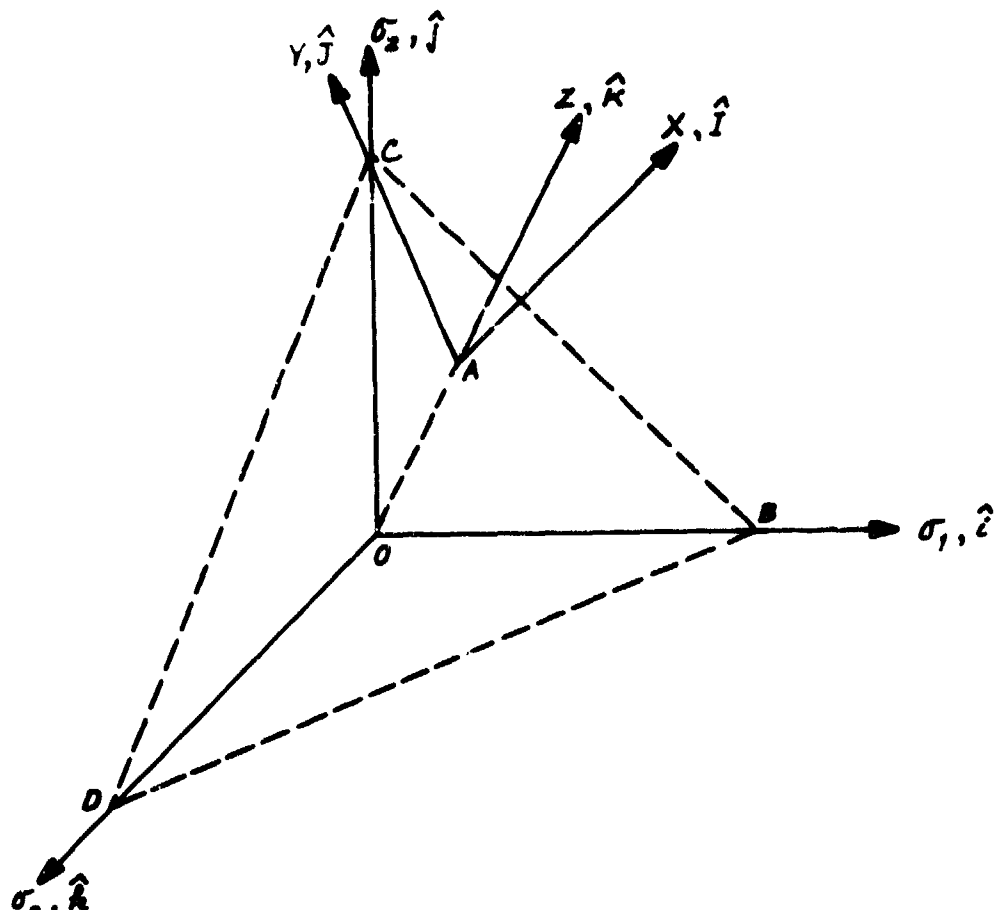


Figure 6-2 PRINCIPAL STRESS SPACE

Figure 6-3 shows the X-Y plane (octahedral plane) with the projections of the $\sigma_1, \sigma_2, \sigma_3$ axes and the intersection with the yield surface for Mohr-Coulomb, Tresca and Mises type yield conditions. With metals, the yield locus is constant with respect to Z, but for soils, it is known that the diameter tends to increase with increasing Z (compressive stresses positive). The triaxial test for compression is represented by a projection on AB while triaxial extension by projection on AE. Furthermore, for an incompressible material, the AX axis represents a projection of the stress path for plane strain results.

Assuming isotropic behavior, in the sense that σ_1, σ_2, σ_3 may be interchanged without changing the material response, then it is necessary to probe only the region bounded by ABE. The triaxial test is probably the most reliable soil test, but as is shown in Figure 6-3, the stress path

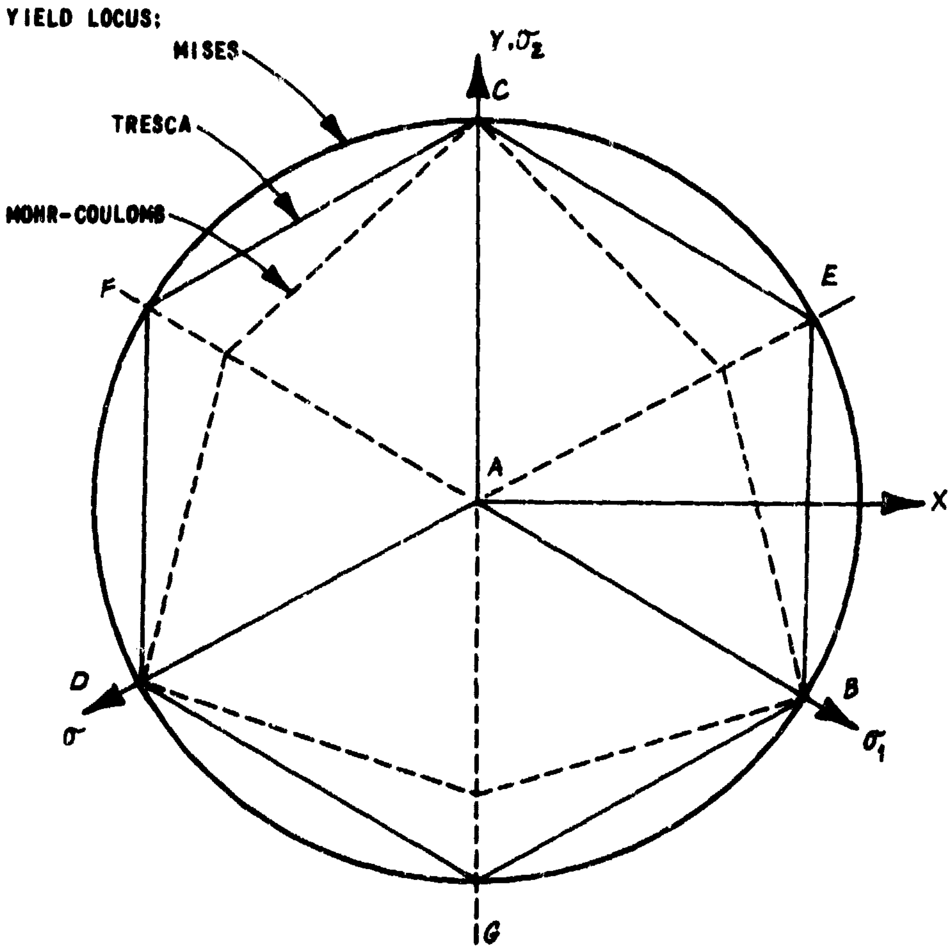


Figure 6-3 OCTAHEDRAL PLANE IN PRINCIPAL STRESS SPACE

departs considerably from conditions of plane strain. Thus, there is a need to develop a plane-strain-type apparatus where control can be exercised over the Y and Z components.

In a similar manner, the plastic or nonrecoverable strain increments may be expressed in a principal strain space. If this strain space is superimposed on the principal stress space, then a strain increment vector can be associated with each stress point. Since only inelastic strains are plotted, loading-unloading tests are required to determine the magnitude of the elastic (recoverable) strains. This has been done, using the triaxial test in compression (projection along AB in Figure 6-3) for fully saturated sands and normally consolidated clays (see Holubec[148], Roscoe and Poorooshasb[149, 150]). The stress space shown here is equivalent to a generalization of the $p-q$ space employed by these authors.

At the present time, more fundamental information is required on the behavior of remolded, partly saturated and overconsolidated clays. Because the triaxial test is the more reliable, such fundamental investigations should be pursued with this equipment. Currently, Cornell University is investigating these problems under a CAL-ORMR subcontract.

Some limited data are available for overconsolidated, fully saturated clays. Figure 6-4, prepared from undrained triaxial test data provided by Cornell University, shows a normalized stress path (P_o the consolidation pressure is used as a normalizing factor) for a normally consolidated and a moderately overconsolidated Weald clay. In Figure 6-4, ($\sigma_1 - \sigma_3$) and P are proportional to distances along AB and Z, respectively, as indicated in Figure 6-2.

Cornell University has also provided some limited data on partly saturated soils. With this kind of experiment, it is very difficult to measure directly the effects of the air phase. Consequently, more analysis of the experimental results are required before specific conclusions can be obtained. Such investigations are presently in progress.

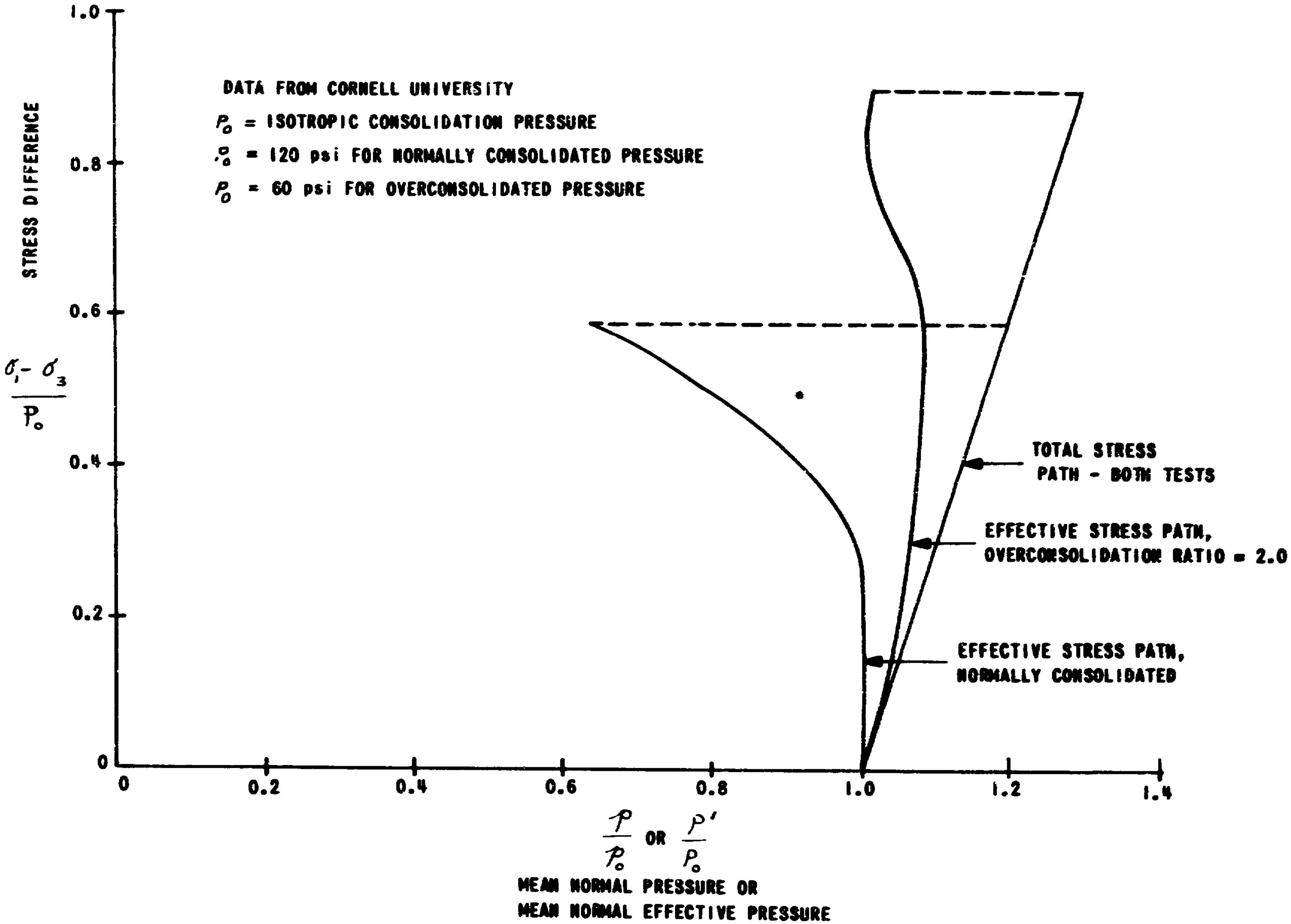


Figure 6-4 COMPARISON OF UNDRAINED, TRIAXIAL TEST STRESS PATHS FOR NORMALLY CONSOLIDATED AND MODERATELY OVERCONSOLIDATED WEALD CLAY

For application of the visioplasticity method to plane strain-type soil mechanics problems, emphasis must be placed on the development of suitable plane strain-type testing equipment. The device should permit variation in the consolidation process, stress path control, failure at large strains and loading-unloading capability. The plain strain apparatus employed by Cornforth[152], Henkel and Wade[146, 153], permits only K_o consolidation. An apparatus recently developed by Ko and Scott[154] provides general stress path control but is limited to small strain. A device which may satisfy some of these conditions has been developed at the McGill University, Soil Mechanics Laboratory[155]. Features of each might be combined to produce a suitable measuring instrument.

6.2 Particle Behavior

Analog soil models consisting of an arrangement of springs and dashpots have been used to describe the bulk behavior of soil in the viscoelastic range.[156] These models have been investigated in the ORMR program so that one or more models could be selected to represent the microscopic behavior of the soil. Such a model would then be useful in predicting the macroscopic behavior of soil via continuum mechanics. At this point of the program it has not been possible to relate the present analog soil models to the microscopic particle-particle description because of specific deficiencies in particle interaction calculations.

The physical parameters, which are pertinent in relating a macroscopic occurrence, such as a vehicle's wheel rolling over a soil, have been listed below. These physical parameters are important because they deal with the change in microstructure resulting from an externally applied load. The approach to formulating an analog mechanical microscopic model must permit incorporation of all significant interparticle forces and all physical changes within the subvolume under consideration.

1. Interparticle Forces
2. Particle Spacing

3. Particle Orientation

4. Particle Size (by cleavage or fracture)

5. Pore Water and Gas Volume

6. Bound and Free Charges

The problem at hand involves the interaction of an external force moving a system initially in equilibrium to a non-equilibrium state. The physical parameters listed help describe the soil in its non-equilibrium state since each parameter will change upon the application of an external load. In the remainder of the section we discuss existing interparticle interaction, theories and the conditions for which they are valid. The role of bound and pore water on interparticle forces as an important effort for off-road mobility research is discussed.

The net force on clay particles is the vector sum of all the repulsive and attractive forces. The repulsive forces are both long range (Coulomb) and short range. Only the former can be varied by change in electrolyte concentrations. The short range repulsive force is attributed to the approach of particles to within a few monolayers of each other and attendant penetration of the bound water. The attractive (Van der Waals) force on any one particle is short range and is relatively independent of electrolyte changes.

To date the accepted methods for calculating particle repulsions use the Gouy-Chapman and the Stern [157] concepts of the charge distributions. These theories are valid in colloid science where external forces are not present and where particle concentrations in the electrolyte are low. In such situations the charge distribution about any one particle is determined by its ability to take on counter ions from the electrolyte and the unique condition that charge equilibrium exists so that the Boltzmann theorem is valid.

The single descriptive feature which is composition dependent is the surface charge density, and indirectly, the chemical exchange capacity. The real nature of the clay particles such as their dielectric constant, shape and crystal type do not enter into the calculations. For example, flat parallel or spherical particle geometrics are typically used in calculations of electrostatic potentials in colloid science.

These calculations for colloid systems are useful in predicting the stability of soils where complete random motion of the particles is possible. In the case of clays existing in nature we find an entirely different situation. Clay particles are usually in non-parallel orientations; consequently, when an external force is applied to the system, the interaction potential of the particles will produce rotation about the particles' centroid. Since free water flow and interparticle potential changes occur as a result of externally applied forces, equilibrium is disturbed and, consequently, non-equilibrium theories apply. Understanding of the non-equilibrium behavior of a clay-air-water system involves the coordination of three disciplines: clay mineralogy, colloid science and clay physics.

The inherent (or structure-insensitive) properties of the clay crystallites determine ion exchange capacity and interparticle spacing at equilibrium. Structure-sensitive properties, such as the degree of crystallite perfection or its defect state, are responsible for surface charge distribution and particle strength. It will be most important for the the interpretation of bulk test results to know whether structure sensitive properties are significant, particularly the extent to which clay particles fracture under load. Indications from our literature search are that such information is not available and will have to be obtained experimentally, e. g. by thin section methods.

Pertinent published experimental results indicate that the volume of bound and free water represents the major factor in a clay water system. The bound water is held tightly by the clay particle; the pressure needed to remove two monolayers of water from its surface is readily calculated, if

only surface tension forces are considered. If the thickness of the monolayer is taken as 2.5 $^{\circ}$A and the surface tension of water as 72 dynes/cm then the external pressure necessary to remove two monolayers of water is 21 kpsi.

It should also be realized that water acts as the vehicle for ion motion in the clay system. Consequently, ion concentration is not only due to charge accumulations on clay particles but also to fluid flow due to external forces on the system. Boundary lubrication between particles may involve fluid flow over the particle surface and direct bound water interpenetration. A clay system without water represents no problem in off road mobility. However, water between the liquid and plastic limits, which describes a Bingham solid, involves inherent latent[158] interparticle forces which can resist clay particle motion. These latent interparticle forces and frictional forces between particles result from Van der Waals and double layer interactions. The main difference in changing from an equilibrium configuration to a non-equilibrium one is in the activation of these interparticle forces by externally applied forces. Therefore, we plan to investigate the mechanism by which these latent interparticle forces are activated in pure clay mineral systems. Since only simple two-particle configurations can be worked with, it will be an advantage to work the problem in reverse; for example, experimentally it is possible to change the surface tension of water, thereby decreasing its workability.[159] Our plan of attack would be to check if microscopic regions under high stress in clay water systems would experience similar decreases in local surface tension and workability.

6.3 Measurement Techniques

The purpose of this effort is to assist in experimental investigation of both bulk and particulate properties of soils.

Observation of thin sections by visual microscopy, electron microscopy and x-ray diffraction appears to offer the best prospect for determining the extent to which particle breakup, change of particle orientation or particle spacing, or other phenomena are responsible for observed changes in bulk behavior. Such fabric or structure studies are based on preparation of thin sections by replacement of the pore water with wax without changing particle position. An essential part of such studies must be that the thin sections are taken from bulk behavior specimens in the regions and at the loads of interest.

Emphasis of the measurement techniques effort during the reporting period was placed on exploration of methods for measuring particle displacement in a soil mass under a moving load.

X-ray and microwave methods for determining soil particle position were explored. The former method is currently used in Canada [147,160] and in England [161]; it is capable of high accuracy but is limited by field size and high equipment and setup costs. Some improvements in the method through use of newer equipment with faster repetition rate (permitting more data points per test) and through denser marker material (providing improved contrast) appear possible. A further attractive possibility would be to obtain soil density, in addition to displacement information in the same x-ray picture. However, scattering phenomena may prevent realization of this idea.

Microwaves of 3 cm wavelength and higher penetrate soil and offer the only other window in the electromagnetic spectrum. Since very few data were available, the absorption and scattering behavior of sand in that region were explored experimentally. Evaluation of these experiments is still in progress.

6.4 Constitutive Relations for Soil as a Non-Reacting Ternary Mixture

In this Section we summarize a brief study performed for CAL ORMR by Dr. S. C. Cowin, Tulane University.[162]

Cowin discusses particulate and continuum models of soil mechanical behavior, and argues for the latter because they more readily allow quantitative solutions. The historical development of continuum theories is traced and it is argued that to fit a time frame of the order of a few years the method chosen must be based on existing theories.

A continuum theory of soil as a non-reacting, ternary mixture (solid, gas and liquid) is recommended by Cowin. In its entirety the theory is believed to be new, though its constituent elements have all been drawn from several sources.[163-173]

The concept of the model provides that each place in an Eulerian frame of reference is simultaneously occupied by a solid soil particle, a water particle and an air particle. Based on this provision, the equations for particle position, particle velocity and the deformation gradients are stated. The density field and the velocities of the three constituents are next formulated in analogy to gas laws. A diffusion velocity for each constituent is stated relative to the mean velocity of the mixture. Porosity is defined as a function of position and time, independent of density and motion.

The total stress in the mixture is defined initially as the sum of the three constituent stresses and three diffusion terms. This stress equation is simplified after discussion of each of its terms. For instance, the stresses in the gas and water phase are recognized as pressures in a

compressible and incompressible medium, respectively, and the solid stress is indicated as the value of a functional over the deformation gradients obtained for the configurations at all previous times. Finally, examination of gas and pore water behavior leads to a simplification of the diffusion terms in the tensor equation for total stress.

Cowin essentially outlined the form of the constitutive relations, though as he points out, a number of elements are missing; for instance his expression for the stress on the solid particle does not yet provide for viscoplastic behavior and expressions for the diffusive forces are needed.

The report concludes with a discussion on implementation. To obtain field equations, the constitutive equations must be combined with the applicable conservation laws. Further, he addresses himself briefly to the boundary value problem and recommends treating a non-rigid wheel making a rut in the soil. An iterative process of analysis and experiment is recommended with some caution against accepting conventional tests (e. g. those disregarding dilatency).

In its present form, the report does not yet permit assessment of the difficulties and problems associated with the methods recommended. We are planning further dialogue with Dr. Cowin in order to assess the desirability of further elaboration of this novel approach.

7. CURRENT RESEARCH ACTIVITIES IDENTIFICATION

One of the objectives of the ORMR program is the acquisition, organization and dissemination of knowledge on off-road mobility and related research. In consonance with this objective, an investigation was made and is continuing, to determine what research programs are currently being conducted by government, industrial and academic organizations. The information obtained will allow CAL to identify problem areas of significance which are not receiving adequate attention and to properly direct its own research efforts.

The Department of Defense Form 1498 Research and Technology (R&T) Resume [174] is the document used by DOD and NASA to report programs in scientific and technical research. A data bank of these resumes at the Work Unit Level (WUL) is maintained by the Defense Documentation Center (DDC). CAL has used this information source to determine ORM relevant research. In addition, resumes of current ORM related research by non-defense sponsoring agencies have been obtained from the Scientific Information Exchange of the Smithsonian Institute and other sources.

A numerical tabulation of the current research projects judged to be relevant, by ORMR technical task area and by major sponsoring organizations, is presented in Table 7-1.

A more detailed summarization of current ORM research programs is contained in Appendix A.

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It is planned to periodically update the WUL DD Form 1498 data as one means of ensuring current awareness of all appropriate sponsored research. Additionally, Project Level Form 1498 data are being sought along with other sources of information for current ORM work.

Table 7-1

SUMMARY OF ORMR CURRENT RESEARCH PROJECTS

SPONSORING ORGANIZATION	ORMR TECHNICAL TASK AREAS					
	SOIL MECHANICS	HUMAN FACTORS	ENVIRONMENT	VEHICLE TERRAIN INTERACTION	SYSTEM REQUIREMENTS & OPERATIONS RESEARCH	VEHICLE & SUBSYSTEM CONCEPT STUDIES
ARMY	6	6	35	23	11	12
USAF	4	3	6	3		
NAVY		1	2	2	1	1
NASA		1				
ARPA	1				1	
OTHERS*	5	5	2	5	2	2
TOTAL	16	16	45	33	15	15

*PROJECTS NOT REPORTED ON DD FORM 1498

8. FUTURE PLANS

CAL's planning of ORMR activities has been guided by the recognition of a logical hierarchical structure for the research process. As was discussed earlier in this report, this structure provides for results, with which to assess mobility, in three categories of varying specificity. Category 1 information will be primarily system oriented or broad scope in nature and is typified by the development and application of a phenomenological model. On the other hand, the data to be found in Category 2 will be more detailed since its source will be vehicle simulators, analysis and experiments. Finally, Category 3 will provide fundamental infromation aimed at describing the basic mechanisms underlying the mobility problem; e.g., CAL/subcontractor investigations in soil mechanics.

A modest expansion of the ORMR experimental effort to be performed in-house by CAL is scheduled for next year. Two vehicles, an M113 and an XM715, have been requested and are being loaned to CAL by the Army for limited testing principally in support of vehicle-terrain-interaction and human factors research. Also hardware elements will be purchased and developed to provide visual simulation of off-road driving situations.

Specific research activities planned for next year are listed on the following pages.

Systems and Operations Research

1. MERS Data Application - The pilot project on vehicle design adaptation using MERS Factor Family maps, initiated in August '67 and involving the cooperative efforts of CAL and Wilson, Nuttall, Raimond Engineers, Inc., will be continued into early 1968.

2. Phenomenological Model - The first version of the phenomenological model will be defined and programmed for implementation on CAL's IBM 360/65 digital computer facility. This will be followed by a program of validation involving comparison of selected model and field test trials. Model applications to specific problems are expected to begin within about one year. Work will also begin on a continuing program of model improvement.

3. Vehicle System Dynamics Model - Guidance will be provided on a continuing basis to vehicle-terrain interaction and human factors efforts toward an integrated dynamic simulation of the off-road mobility process.

4. Technical Liaison - It is proposed to establish and maintain direct channels of technical information exchange and cooperation with the military and other appropriate agencies, with particular reference to phenomenological model: data inputs, field testing needs, and applications in support of military concept and design studies.

5. Requirements Studies - The acquisition and analysis of information on military off-road vehicle requirements, advanced planning and tactical doctrine will be continued through this next period.

6. Vehicle Case Studies - This present study, of selected vehicles from RDT&E phases through details of operational experience, will be completed during the ensuing year.

Vehicle-Terrain Interaction

1. Vehicle-Terrain Modeling - An initial dynamics simulation model of the vehicle-terrain system will be implemented and validated during the next year. Work also will be initiated on a subsequent modeling phase to provide improved realism and increased scope of configurational applicability.

2. Soil Trafficability Theories - A critical evaluation of existing theories of soil trafficability will be conducted with the objective of establishing their regimes of acceptable prediction.

3. Field Test Practices - This recently initiated review of existing off-road vehicle field test practice will be completed during the coming year and is expected to provide recommendations for improved and standardized procedures.

4. Structural Loading and Reliability - The ongoing study of current practice in structural loading design criteria and reliability requirements, leading to recommended quantitative criteria, will continue through the coming year.

5. Vehicle Performance Studies - Applications of the validated vehicle-terrain dynamics simulation model, as well as engineering analysis of performance where feasible, will be made to provide inputs for phenomenological modeling as well as to contribute toward rational vehicle design processes.

Human Factors

1. Off-Road Driving Simulator - The detailed needs, within human factors research and off-road vehicle systems dynamic modeling, for providing a simulated driving environment in the laboratory will be assessed. A plan for evolutionary development of such a simulator to be incorporated into the loop with the Vehicle Systems dynamic model will follow. It is expected that a limited visual-field-only simulator will be developed as a first step.

2. Degraded Visibility Effects - The program of experimental study relating degraded visibility to off-road driving performance (notably speed of advance) will progress to vehicle field experiments, as well as to driving simulator runs as soon as the laboratory equipment becomes available (and validated within this context).

3. Vibration and Other Stress Effects - Detailed study of the effects of vibration and shocks, temperature, humidity and noise level will be made this coming year. The investigations will involve test planning followed by testing in the field as well as on the simulator. (Vibration and shock studies in the laboratory cannot begin until suitable motion response has been incorporated into the off-road simulator.)

4. Decision-Making Study - The current investigation into the detailed nature of decision making by the driver/commander will continue at a low level.

5. **Auxiliary Information Displays** - The slipmeter experiment (directed toward assessment of the value of auxiliary informational aids) will be completed and analyzed this year. Consideration will be given to the desirability of studying other augmenting information concepts.

Environmental Factors

1. World Data Base - Assessment of the world environmental data base, which has been underway from the outset is viewed as a continuing effort which is expected to provide by the end of the coming year an adequate inventory of already available environmental data for mobility purposes. Follow-on work will concentrate in areas in which the existing data base is considered inadequate.

2. Interrelation, Prediction, and Application - Work directed towards: 1) predicting soft-soil conditions from climatic, soils, and terrain data; 2) predicting stream-exit problems and their severity from terrain features; and 3) establishing relations between non-engineering and engineering soil classifications will continue and is expected to be completed in the coming year. The study of relations among other environmental factors will be initiated in the coming year. In addition, work will be initiated to isolate independent descriptors of the environment with a view toward formulating a minimum set of such descriptors. The methods of principal factor analysis and related methods will be applied to factors affecting soft-soil prediction, slope analysis, and other environmental descriptors.

3. <u>Descriptive Methodology Studies</u> - Effort directed toward development of a unified methodology for statistical description of the terrasphere will be initiated in the coming year. In particular, we will undertake the following:

a) Formulation of a field theory of the terrasphere.

b) Definition of derived quantities relevant to mobility; these fields will be obtained through such operations as differentiation (e.g., obtaining slope fields from terrain elevation fields) and averaging.

c) Determination of appropriate induced statistical distributions of environmental parameters.

d) Formulation of sampling plans and measurement techniques which properly reflect the field structure appropriate to the mobility process. For example, slopes derived as an average over distances much larger than vehicle scale will not reflect ORM needs for slope data.

4. <u>Data-processing and Modeling</u> - This activity will continue with emphasis on the development of:

a) Rapid methods for digitizing environmental data.

b) Computer programs for manipulating environmental data and displaying them in meaningful form such as maps, frequency histograms, and graphs.

c) Statistical processing procedures to provide inputs for the exercising of phenomenological mobility models.

Soil Mechanics

1. Application of Visioplasticity Methods - Planning has been underway for an analytical - empirical effort at applying visioplasticity methods to the prediction of soil response under complex loading. This program will be implemented for one selected soil and loading configuration and will comprise:

   a. Stress-strain time measurements over restricted regions of stress space.

   b. Velocity measurements under specified loading.

   c. Soil structure and fabric analysis of thin section measurements in failure regions.

   d. Visioplasticity analysis yielding stress field and energy dissipation calculations.

   In continuation efforts extending beyond the coming year the application of such results to prototype prediction by scaling and approximate analysis will be pursued.

2. Fundamental Studies - These are continuing efforts aimed at supporting and generalizing on visioplasticity or any other specific approaches.

   a. Soil physics - particle interactions and relations among solid, liquid, and gas phases.

   b. Generalized bulk material response - extension of stress-strain-time equations to generalized loadings.

c. Mechanics methods and principles - scaling laws, numerical analysis, etc.

d. Continuing awareness of pertinent progress in soil mechanics research.

Program Management

Technical Management Functions - In order to implement and sustain the research described above, the CAL ORMR Program Office will continue the technical management functions enumerated below:

1) Review and organize existing knowledge on ORMR as it meets users' needs.

2) Maintain long-term ORMR plan.

3) Implement, monitor and evaluate results of ORMR.

4) Disseminate research results and relate to users.

5) Develop and maintain files on ORMR projects.

6) Assist ARPA with technical review of proposals and related work.

7) Provide technical and administrative support to ARPA.

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APPENDIX A

SUMMARIES OF CURRENT RESEARCH PROJECTS PERTINENT TO OFF-ROAD MOBILITY

SUMMARY INFORMATION ON SOIL MECHANICS

TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Solutions to Problems of Soil Mechanics	ARPA	Brown University	Load bearing capacity of soil, rock and concrete is calculated by upper and lower bound technique and solutions are interpreted.
Development of X-ray Techniques for Detecting Soil Motion	AF Weapons Lab	U. of New Mexico	Development of a multipulse x-ray device to determine time history of soil particles under dynamic load.
Behavior of Granular Media	ATAC	U. of Michigan	Develop stress-strain relations based on ideal plasticity or on other non-linear, non-elastic systems.
Unified Study of Shrinkage and Consolidation Phenomena in Soils	ARO (Europe)	Negev Inst. of Arid Res., Beersheba, Israel	To contribute to the knowledge on the effects of shrinkage and consolidation on soil volume changes.
Research Studies in the Field of Earth Physics	WES	MIT	Study physics and behavior of particulate multiphase soil systems to determine (1) mechanisms of strength generation in natural and artificial soils (2) influence of environmental factors such as atmosphere, pore fluid and temperature on stress-strain behavior.
Evaluation of Constant Volume Techniques for Accelerating Determination of Shear Strength in Terms of Effective Stress	WES	WES	The validity of constant volume shear tests will be studied experimentally.
Experimental Studies of the Response of Soils to Ground Shock	WES	WES	1) Study stress strain behavior of soils under shock loading 2) Development of test techniques 3) Lay basis for design of underground structures.

(Continued)

TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Studies of Dynamics of Macroparticles in Shear Failure of Soil Masses	AFCRL	Princeton U.	Theory of macromeritic solid and liquid states applied experimentally and analytically to study of shear resistance and deformation of non-cohesive macro particles.
Role of Clay Minerals in Landslide Movements and Measurement of IR Reflection Properties of Clay	AFCRL	Columbia U.	Correlation of clay mineralogy and physical properties, including their fluctuations under environmental influences as a prerequisite to terrain analysis and description.
Mechanics of Soil Surfaces	AFCRL	AFCRL	Shear Failure Modes and Physics characteristics of soil loaded by moving aircraft. Prediction of deformations based on soil characteristics in laboratory simulation.
Applied Rheology of Frozen Soil	CREEL	Dartmouth College	Design special laboratory equipment and techniques and determine rheological properties of soils at low temperatures.
Measurement and Characterization of Physical Properties of Soil as Related to Tillage Implements and Tractive Effort	U.S. Dept. of Agriculture	Nat. Tillage Machinery Lab.	Search for new and better methods of measurement and characterization of physical soil properties (e.g. structure, strength and stability) as related to physical forces applied by agricultural implements.
(NOT GIVEN)	NSF	Cornell U.	Effective Stress Determinations.
(NOT GIVEN)	WES, ONR	Cornell U.	Electro Kinetic Studies.
Remote Soil Strength Measurement	AFCRL	Princeton U.	Formulation of a rheological model of soil behavior and remote measurement of pertinent parameters.

(continued)

TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
(NOT GIVEN)	Canadian Defense Research Board	McGill University	Stress-strain relations of soils under dynamic loading.

SUMMARY INFORMATION ON HUMAN FACTORS

TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Definition of the Interaction between Vibration and Prolonged Acceleration	Wright-Patterson AFB	Wright-Patterson AFB	To define both biomechanical and physiological interactions when vibration is superimposed on steady state prolonged acceleration.
Performance Physiology	USA, Medical R&D, Washington, D. C.	USA Medical Research and Nutrition Lab. Fitzsimmons Gen. Hosp., Denver, Col.	To develop a better understanding of the basic aspects of physical performance in relation to age.
Biomechanical Aspects of Performance	USA Medical R&D, Washington, D. C.	USA Medical Research Lab., Ft. Knox, Ky.	To develop techniques to measure human strength and endurance in heavy work situations, study factors in work situation control design, body positions, supports, etc., which influence efficiency, derive general principles which would help in understanding and predicting work efficiency, study the contribution of personality factors to individual differences in susceptibility to performance decrement.

(Continued)

TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
The Discrimination of Visual Signals Expected in Aircraft Operation with Competing Signals Contingencies	USA Med. R&D, Wash. D. C.	Indiana Univ. Foundation Bloomington, Ind.	The operator of an airborne vehicle depends on the perception of a spatial relationship of himself to his vehicle and of the vehicle to selected points or objects in the environment. These perceptions determine control settings with modifications dependent on a closed loop visual feedback system which can be interrupted by sudden change stereopsis, then becomes the decision basis for control responses.
The Measurement, Composition, and Stability of C	USA Med. R&D, Wash. D. C.	USA Med. Res. Lab, Ft. Knox, Ky.	To develop procedures for measuring the components of complex skills to identify basic abilities both general and specific to a variety of skills to observe revealed ability patterns under conditions of practice and stress to test the regression hypothesis in performance decrement.
Human Vibration Research/Automotive Engr. Investigation Studies	U.S. Army Tank-Auto Ctr. Warren, Mich.	USATAC Adv. Sys. and Conc. RD	Determine the human tolerance limits to linear and angular random and sinusoidal vibrations encountered in military ground vehicles, develop the necessary instrumentation to implement testing in pitch, roll, and vertical motions.
Vehicle Vibration Research/Automotive Engr. Investigation Studies	U.S. Army Tank-Auto. Ctr.	USATAC Adv. Sys. and Conc. Res. Div. Warren, Mich.	Develop an analytical procedure to measure the mechanical and subjective response of humans to random vibratory environments.

(Continued)

TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Lunar Surface Scientific Mission Simulation (Phase II)	George C. Marshall Space Flight Center	----	To experimentally validate, under near operational mission simulation of a 1-3 days in duration, locomotion control and display criteria, habitable volume, duty-station layouts, and intra- and extra-vehicular task performance for lunar surface roving vehicles.
The Measurement of Stress and Its Relationship to and Effects on Human Performance in Mental and Motor Work	Office of Naval Research, Wash, D. C.	Miami-Ohio State U.	Studies on various type of stressors on the bioelectric responses of human subjects will be continued and related to concomitant motor and mental performance.
Research on the Effects of Vibration on Visual Acuity and Dial Reading Performance	Wright-Patterson AFB	Cornell Aeronautical Laboratory, Inc.	To provide information of the effects of vibration of the type encountered in aerospace systems upon operator performance capabilities.
Integrated Seat and Occupant Restraint Performance	Department of Transportation	Cornell Aeronautical Laboratory, Inc.	Investigate Motor Vehicle Safety performance standards as they relate to integrated passenger seat and occupant restraint.
Occupant Protection In Vehicle Interior	Department of Transportation	Cornell Aeronautical Laboratory, Inc.	Develop a technical data base and a plan for outlining goals for establishing future minimum acceptable motor vehicle interiors from a crash worthiness standpoint.
Research on the Effects of Vibration on Dial Reading	USAF, Systems Engineering Group	Cornell Aeronautical Laboratory, Inc.	Determine the effects of sinusoidal vibration upon human visual performance relating to the speed and accuracy of obtaining quantative information from dial type instruments and determine ranges within which results of further more complete study might follow.

(Continued)

TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Evaluation of the Wrist-Twist Steering Concept for Automobiles	Ford Motor Company Dearborn, Michigan	Cornell Aeronautical Laboratory, Inc.	Produce a comparative evaluation of three kinds of automobile steering systems.
Research on the Effects of Vibration on Visual Acuity and Dial Reading Performance	Systems Engineering Group; Wright Patterson AFB; Ohio 45433	Cornell Aeronautical Laboratory, Inc.	The purpose of this investigation is to determine the relationship between relative displacement of the eye and the visual acuity and dial reading performance.

SUMMARY INFORMATION ON ENVIRONMENTAL FACTORS

TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Landforms and Environmental Processes	AFCRL	AFCRL	To investigate morphology and characteristics of landforms, especially desert and tropical environments.
Site Monitoring	AFCRL	AFCRL	To monitor selected sites throughout the year -- measurements include soil strength and moisture content.
Airborne Electromagnetic Sensing	AFCRL	WES	To obtain terrain information by electromagnetic sensing.
Performance of Selected Site Studies for Terrain Properties Throughout the USA	AFCRL	Boston College	Investigation of reflectance properties of terrain and correlation to air photographs.

(continued)

TITLE OF PROJECTS	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Study of Hydrologic and Mineralogic Data of Dry Lake Beds to Determine Cause of Fissure Formation	AFCRL	University of Massachusetts	To study dry lake bed and deserts and air photo recognition techniques.
Airborn Infrared Sensor Data Interpretation to Evaluate Instrumentation for Determining Physical Properties of Natural Terrain	AFCRL	Naval Research Labs.	No work statement available.
Infrared Sensing, Airborne	ONR	AFCRL	To investigate potentialities of infrared sensing.
Terrain Evaluation of Fort Greely Automotive Test Course	U. S. Army Artic Test Center	WES	To map and evaluate major elements of Ft. Greely test course. Factor families were mapped.
Evaluation of Classified SLAR Imagery for Military Geographic Intelligence	USAEGIMRADA	Raytheon Co.	To analyze SLAR imagery and determine extent it can be used for extraction of information required for production of Military Geographic Intelligence.
Quantification of Terrain Factors for Ground Mobility Purposes	WES	WES	To develop procedures for describing attributes of terrain for selected areas in Thailand.
Soil Moisture - Strength Characteristics, Thailand	WES	WES	To obtain soil moisture and strength relationships.

(continued)

TITLE OF PROJECTS	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Trafficability Classification for Thailand Soil	WES	WES	To obtain soil trafficability types based on USAA System.
Comparison of Temperature and Tropical Soils	WES	WES	Field and lab comparisons of temperate and tropical soils.
General Environmental Studies	WES	WES	To develop quantitative methods of predicting effects of environment on men and materials.
Research in Earth Physics - Military Evaluation of Geographic Areas	WES	WES	To test, evaluate and modify existing systems for quantitative description of the environment. Also, to study tropical soils.
Mobility Terrain Analysis and Symbology	WES	WES	Investigate remote sensing of terrain characteristics, soil type, moisture content and strength, vegetation type and density, surface geometry which affect mobility.
Earth Physics and Surface Mobility	WES	WES	Research in Surface Media-Weather Relationships.
Earth Physics in Terrain Analysis and Symbology	WES	WES	Increase remote sensor knowledge.
Vertical Velocity Distribution in Streams	WES	WES	To develop mathematical relations between bed roughness characteristics and vertical velocity distribution in streams.
Tropical Soils Study in Costa Rica	WES	Inst. Costaricense de Elec.	To collect data on soils, topography, vegetation and weather at sites in Costa Rica; to develop methods for classifying terrain from a mobility standpoint and predicting soil trafficability.

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TITLE OF PROJECTS	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Pedological. Characteristics of Soils of Selected Areas in Thainland, Great Soil Groups	WES	Kasetsart University, Bangkok	To describe and present general soil characteristics maps.
Pedological Characteristics of Soils of Selected Areas in Thailand, Soil Series	WES	Development Dept. - Soil Survey - Kasetsart University Bangkok	Prepare and present maps and accompanying text of soils on the soil series level.
Acquisition of Aerial Photography of Selected Areas in Thailand	WES	Lyons Associates, Inc.	To obtain new area photographs of selected areas in Thailand
Vegetation Mapping of Puerto Rico	WES	New York Botanical Garden	To classify the natural vegetation of Puerto Rico and prepare key to identify vegetation structures from air photos.
Characterization of Water Tables in Oregon Soils with Reference to Trafficability	WES	Oregon State University	Quantitatively describe and compare water table regimes and correlate to soils.
High Altitude Research - Central Asian Highlands	Natick Labs	Natick Labs	To prepare resume of environmental conditions above 2000 meters with emphasis above 3000 meters.
Terrain Analysis Related to Vehicle Mobility	Natick Labs	Natick Labs	To determine the character and occurrence of various types of terrain features that will prevent or impede the off-road movement of military vehicles.
Study of Humid Tropics	Natick Labs	Natick Labs	To identify, characterize, classify and map major environmental types and sub-types, in the humid tropics, on the basis of military significance.

(Continued)

TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Study of Desert Areas of the World	Natick Labs	Natick Labs	To identify, characterize, classify and map major environmental types in desert areas of the world on the basis of military significance.
Thematic Mapping of Militarily Significant Information for Southeast Asia	Army Natick Labs	Natick Labs	To publish an atlas of maps on Southeast Asia.
Climatic Analog - Southeast Asia	Natick Labs	Natick Labs	To determine climatically analogous areas in Southeast Asia and other low-latitude areas in the world.
Tropical Terrain Analysis	Natick Labs	Natick Labs	To obtain quantified tropical data from field and lab studies for development of terrain design criteria.
Basic Environmental Data Research - Thailand	Natick Labs	Natick Labs	To obtain detailed environmental data and analyses at tropical locations in Thailand, and also to increase Thai capability for conducting environmental research.
Mountain Environment Transect Study - Colorado and Utah	Natick Labs	Univ. of Colorado	To study ways in which environmental features of the natural landscape interact with one another, and to correlate to aerial photographs.
Classification and Characterization of Humid Tropical Environments	Natick Labs	Denver University	Locate and map types and subtypes of humid tropical climate.
Inventory of Geographic Research on the Humid Tropical Environment	Natick Labs	Texas Instruments Inc.	To provide an evaluated inventory of the status of environmental research and knowledge on humid tropical regions of the world.

(Continued)

TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Study of the Physical Properties of Soils Through Interpretation of Aerial Photograph E721	Army Research Office, Europe	Inst. Edafolgia Biologia Vgtl, Spain	To improve the usefulness of landscape characteristics as a tool for identifying the physical characteristics.
Use of Vegetation as an Indication of Soil Properties Under Desert Conditions	Army Research Office (Europe)	Negev Institute for Arid Res. (Israel)	To increase knowledge concerning reliability of plant communities as indicators of soil properties.
Comparative Study of the Pattern of Land Use in Relation to the Geomorphic Features of Terrace Uplands in JAPAN.	Army R&D Group (Far East)	Faculty of Literature and Eduation - Ochanomizer, Univ. Japan	To study the terrace uplands of Japan - and interrelationships of land use and visible characteristics of landscape.
Ecology of Tropical Delta Forest Environment	ARO, Durham, N. C.	Smithsonian Institute	To improve knowledge of tropical delta forest environment.
Soil Strength Measuring Devices	U.S. Army Tank Auto Center	U.S. Army Tank - Auto Center, Land Locomotive Lab.	To determine the feasibility and practicality of various soil measuring equipment for obtaining inputs to equations of soil-vehicle relationships.
Soils Mapping Techniques	U.S. Army Tank - Auto Center	USATAC Land Locomotion Lab.	To develop technology of predicting soil strength.
Directory of Humid Tropical Research Institutions	OCRD	McGill University	To provide a directory of all institutions throughout the world that conduct significant research programs on the Humid Tropics.
Bio-ecological Classification for Military Environments Found in Tropic Latitudes	OCRD	Wilson, Nuttall, Raimond, Engineers, Inc.	To test applicability of Holdridge life zone system to the description and classification of samples of tropical terrain.

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TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Drainage Pattern Evolution	Office of Naval Research	Iowa Eng. Experiment Station	Study of conditions governing the formations and enlargement of stream channels. A model has been devised to predict erosion and landscape change and is being tested.
VTOL Landing Site Study	System Engineering Group (USAF)	Cornell Aeronautical Laboratory, Inc.	Analytical Study covering application of quantitative terrain information to landing site distribution studies and to penetration analyses efforts.
ARPA Multiband Photographic & Infrared Reconnaissance Test- Phase III	Rome Air Development Center	Cornell Aeronautical Laboratory, Inc.	Through a series of experiments in Thailand, and other sites, evaluate multiband, oblique and panoramic photography as it is applied to reconnaissance and intelligence in guerilla or counterinsurgent warfare.

SUMMARY INFORMATION ON VEHICLE-TERRAIN INTERACTION RESEARCH

TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Measurement of Landing Loads on Aircraft	USA Av. Mat. Lab	Douglas Aircraft	Development of math. model that can predict landing loads for Army aircraft.
Environment Research for Optimum Equipment Design	USA Engr. R&D Lab	USA Engr. R&D Lab	Provide project engineer with optimum environment design criteria.
Shock and Vibration Program	Army Elect. Command	Army Elect. Command	Determine shock and vibration environments of equipment installed in military vehicles.
Mobility Fundamentals and Model Studies	USA CE WES	USA CE WES	Develop fundamental relations between vehicles and media upon which they move. Relations will permit the determination of effects of vehicle weight, tire or track dimensions, tire pressure, etc., on speed, slip, drawbar pull, and rolling resistance on a wide variety of soils.
Research in Earth Physics - Mobility	USA CE WES	USA CE WES	Obtain data and develop hypotheses and theories on interaction of soil and moving loads.
Further Development of Load Flow Theory for Soils	USA CE WES	USA CE WES	Check and extend wheel theory and conduct lab tests aimed at development of improved penetrometer.
Reliability Research	Army Res. Office	RAC	Research and analysis to study advances in science and technology for improving military capabilities and operations.

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TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Preparation of Guide Report on Engineering Concept Evaluation of Terrain-Vehicle System	Army Research Office	GM, Santa Barbara	Further improvement of quality and quantity of information on terrain-vehicle relationships
Performance of Traction Elements (Track Tension)	ATAC	ATAC	Develop relationship between soft soil performance and characteristics of traction elements. Experimental approach will take into account suspension. Design guides developed.
Gun Tube Dynamics	ATAC	ATAC	Develop simulation technique to analyze effect of ride vibration while firing on the move. Realistic field of view to be included.
Mechanized Data Reduction	ATAC	ATAC	Develop data reduction techniques to implement reporting of computer and field test results. Continuous data reduction in the form of spectral density, peak distribution, and rms information.
Vehicle Vibration Profile	ATAC	ATAC	Obtain complete vibration spectrum of tracked vehicles over a variety of terrains.
Determination of Combined Climatic Vibration Parameters	ATAC	ATAC	Determination of degree of interaction of factors of combined environments, i. e., vibration, shock, temperature, etc.
Soil Properties of River Banks	ATAC	Detroit University	Investigate river entry and exit problem of amphibious vehicles by use of scale models.

(continued)

TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Studies of Vehicle Motion Over Rough Terrain	ATAC	Midwest Applied Science Corporation	Develop methods for description of ground roughness and relate vehicle and human response to form of ground roughness, etc.
Scaled Vehicle Mobility Evaluation by Field Type Methods	ATAC	Southwest Research Institute	Devise methods for rapid and economical evaluation of vehicles and vehicle components, establish scaling laws.
Amphibious Vehicle Advanced Study/Design	Marine Corps	Army Materiel Command	Isolate hydrodynamic forces and moments affecting high speed control in water of airoll vehicle concepts through scale water model.
Tracked Amphibious Testing	ONR	Selwood Research, Inc.	Prepare handbook covering engineering and user tests of tracked amphibious vehicles.
A/C Dynamic Loads from Substandard Landing Sites	AF FD Lab	Boeing Company, Airplane Division	Develop methods for analyzing the dynamic response of Aircraft on unprepared landing sites: generate engineering description of roughness, formulate design criteria.
Study of Experimental Wheel	USA WES	WES	Verify hypothesis that ability to control stress distribution on tire/soil means better performance.
Fourier Series Description of Terrain	USA Engineers, WES	FMC	Develop mathematical parametric model of vehicle dynamic response to surface geometry.

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TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Road Roughness and Serviceability Investigation	Ky. Dept. of Hwys. US BPR	Ky. Dept. Hwys.	Measurement and evaluation of the effect of pavement-surface characteristics on comfort of passengers. Automatic system, using accelerometer, designed. Report issued: Accelerometer Method of Riding Quality Testing, R. L. Rizenbergs, Ky. Dept. of Highways, February 1965.
Basic Studies of Traction and Transport Devices	USDA	Auburn U. & Others	Determine the effect of design factors and methods of operation of traction and transport equipment upon the performance of the equipment and evaluate effect of resultant forces and deformation of soils.
Equipment for Establishment and Maintenance of Roadside Cover	Ill. Div. Hwys.	U. Illinois	Develop equipment for roadside cover operations; study tractor-chassis design parameter; mathematical model written for vehicle in motion -- on digital computer.
Effect of Design Factors on Traction	USDA	Auburn U. and Others	Determine and evaluate tire and track design.
Mathematical Analysis of Hydroplaning Phenomena	Department of Transportation	Cornell Aeronautical Laboratory, Inc.	To develop an improved mathematical analysis which quantitatively predicts the actions that occur when a highway tire rolls or slides on a pavement surface which is covered with a water film and all or part of the normal force is supported by hydrodynamic pressures.

SUMMARY INFORMATION ON
SYSTEMS REQUIREMENTS AND OPERATIONS RESEARCH

TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
The Tank Weapons System	CDC Armor Agency	Ohio State University	To assess the effect of tank design characteristics on tank performance in order to assist military planners in preparing QMR's.
Development of a Quantitative Cross-Country Mobility Prediction System	WES Army Engineers	WES Terrain Analysis Branch	To establish the effects of terrain factors on vehicle performance (speed made good, fuel consumption, and dynamic response) and to develop an analytical method of estimating the performance.
Surface Mobility	WES Army Engineers	WES Mobility Research Branch	Determine the relation between environment and vehicle performance, using simple methods of both contact and non-contact measurements for rapid employment under combat conditions.
Battlefield Day Course/ Automotive Engineering Investigation Studies	ATAC	ATAC Adv. Sys. and Concept Research Div.	Determine vehicle combat mobility performance by mathematical models and tests.
Concept Studies/Investigations of Future Transport Vehicles	ATAC	ATAC Adv. Syst. & Concept Research Division	To maintain a general long range transport vehicle research and exploratory development effort.
Investigation of Transport Vehicle Dynamics/Trans Veh. Adv. Design	ATAC	ATAC Adv. Syst. & Concept Research Division	Develop methods for evaluating the performance and effectiveness of ground transport systems.

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TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Investigation of Transport Vehicle Dynamics/Transport Vehicle Advanced Design	ATAC	ATAC Adv. Syst. & Concept Research Division	Develop methods for evaluating the performance and effectiveness of ground transport systems.
Concept Studies for Future Combat and Special Purpose Vehicles	ATAC	ATAC Adv. Syst. & Concept Research Division	To continually probe advances in state-of-the-art technology for feasible application to future combat and special purpose vehicles, as model studies and physical science activities progress along with the successful completion of component development, new vehicle concepts can be accomplished. This activity provides the initial concepts from which sound vehicular programs and approaches can be established.
Engineering Test and Evaluation of Foreign Equipment	ATAC	TECOM	To compare foreiga against comparable U.S. equipment and determine features and quantitative data for incorporation into U.S. designs.
Improved Delta Mobility	Office of Naval Research	Westwood Research, Inc. Los Angeles, California	1) Assess cost-effectiveness of water craft and vehicles for achieving immediate improvements in mobility of specified types of forces in the Mekong Delta. 2) Assess performance potential of advance platform concepts for improved mobility in Vietnam. 3) Assess nature of environmental conditions affecting mobility in selected delta riverine areas where probable requirement for counter-insurgency operations is high.

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TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Concept and Feasibility to Improve the Mobility, of Towed Artillery	Rock Island Arsenal	Lockheed Aircraft Service Co, Ontario, California	To provide concept and feasibility studies to improve the mobility of the present and future towed artillery weapon.
Phase II of a Long-Term Off-Road Mobility Research Program 6844	Army Res Office (Durham)	Cornell Aeronautical Laboratory, Inc.	Tech Objective - Achievement of improved understanding and methods in off-road mobility and the translation of these into such forms as could be directly applied by such users as strategic planners and vehicle operators.
Research in Vehicle Handling Properties	Department of Transportation	Cornell Aeronautical Laboratory, Inc.	To improve the data base for establishing standards in safe handling standards for automobiles.
Automobile Steering Systems and Force-Controlled Vehicle Dynamics	General Motors Corp. Detroit, Michigan	Cornell Aeronautical Laboratory, Inc.	To conduct theoretical and experimental research on automobile steering systems, force-controlled vehicle dynamics and handling qualities.
Parametric Design/Cost Effectiveness Study for MICV-70	New York Procurement District (US Army)	Cornell Aeronautical Laboratory, Inc.	Perform a parametric cost/design effectiveness study for the MICV-70.

SUMMARY INFORMATION ON
VEHICLE AND SUBSYSTEM CONCEPT STUDIES

TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Ultra High Speed Electric Propulsion Test-Bed Vehicle Comparison and Evaluation	USA RDL Ft. Belvoir	FMC	Integrate electric propulsion components into working vehicle. Test and evaluate electric and conventional vehicle. Develop performance and produce computer program for electric propulsion system.
Mobility Augmentation of M113 APC	USA Lim. War Lab. AGP	USA Lim. War Lab. AGP	Improve mobility of M113 in tropical areas where water obstacles are frequently encountered.
Advanced 1/4 Ton Utility Truck, Swimming	ATAC	ATAC	Exploratory development of various unique and unconventional approaches to floatation and water propulsion of 1/4 ton vehicles.
Non-Metallic Spring/ Mobility Systems	ATAC	ATAC	Develop mechanical springing media to allow major increase in wheel travel to i[illegible]rove mobility. Fiber-glas fila[illegible]ts to be applied to torsion bars.
High Yield Torsion Bar	ATAC	ATAC	Develop mechanical springing media to allow major increase in wheel travel. Use alloys known as ausform and marage.
Hydro-Pneumatic Suspension System	ATAC	ATAC	Provide fully-developed and tested all-terrain and all weather suspension system for tracked systems.

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TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
Torsion Bar and Tube Suspension System	ATAC	ATAC	Develop torsion bar and tube suspension incorporating variable ground clearance, suspension lock out, high wheel travel, etc., for adaptable mobility.
Measure Profile and Crushability of Terrain Optically	ATAC	Emerson Electric	Develop means of measuring terrain profile to adapt vehicle through active suspension system.
Evaluation of New Ground Mobility concept	ATAC	Grumman	Investigate new concepts which appear to offer increased vehicle off-road mobility.
Active Suspension	ATAC	Westinghouse Electric Undersea Division	Develop suspension system that will provide ride control and gun platform stability.
Studies of Vehicle Morphology	ATAC	Wilson, Nuttall, Raimond, Engineers, Inc.	Establish optimum vehicle forms based on requirements of terrain, vehicle mission, and effectiveness.
Coupled Mobility Device	ATAC	Stevens Institute	Determine military potential of coupled military device (CMD) comprising a multiplicity of powered units operable coupled or singly.
State-of-the-Art Review of Amphibious Surface Vehicles	Office of Naval Research	Cornell Aeronautical Laboratory, Inc.	A state-of-the-art review of current and future amphibious surface vehicles will be prepared which will define physical characteristics and performance capabilities of production and research amphibious vehicles of the Marine Corps and the Army. Emphasis will be placed on the following physical characteristics:

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TITLE OF PROJECT	SPONSORING ORGANIZATION	RESEARCH ORGANIZATION	RESEARCH OBJECTIVES
State-of-the-Art Review of Amphibious Surface Vehicles	Office of Naval Research	Cornell Aeronautical Laboratory, Inc.	(Cont'd) hull, track, propulsion systems, suspension systems, methods of obtaining waterborne lift and controls. An attempt will be made to evaluate performance capabilities of the candidate amphibious vehicles on the basis of existing test results and field operating experience. Recommendations will be made that relate future research and development effort to the long range needs of the marine corps amphibious operations capabilities.
Crash Worthiness of Vehicles Structures	Department of Transportation	Cornell Aeronautical Laboratory, Inc.	To develop the capability to predict a motor vehicles crash worthiness in the design stage.
Mailster Use in Cold Weather Regions	U.S. Post Office Dept. Office of Res & Engr. Wash. D.C.	Cornell Aeronautical Laboratory, Inc.	To determine the performance characteristics of the 1/4 ton, three wheel vehicle in extreme cold climate.